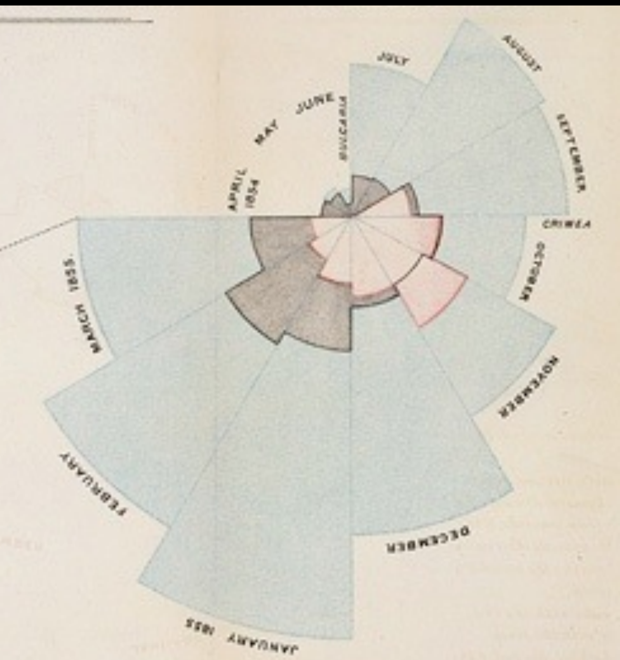
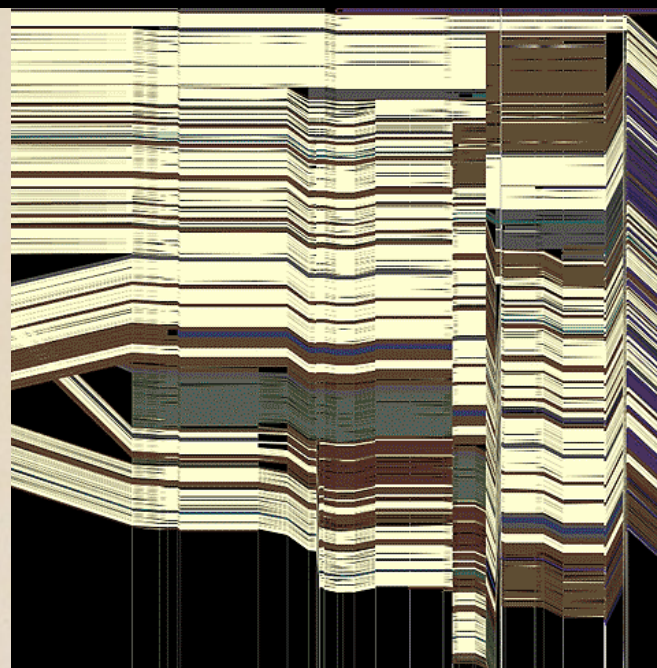
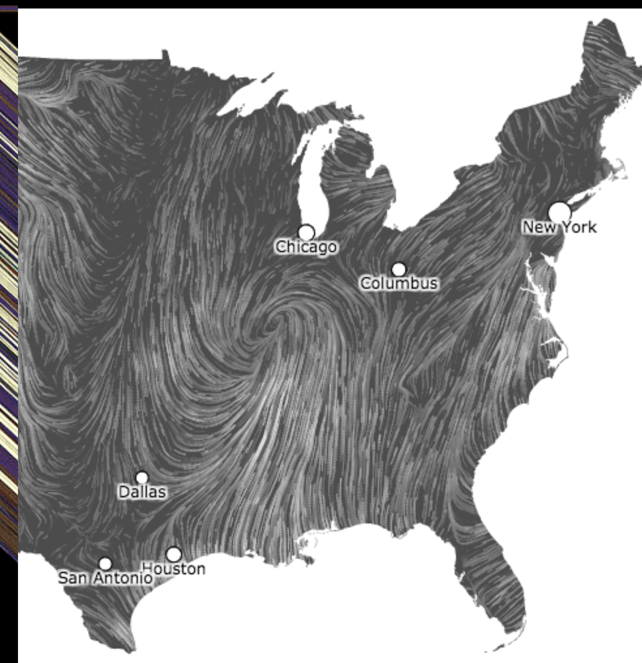
# **CSE 442** - Data Visualization

# Color



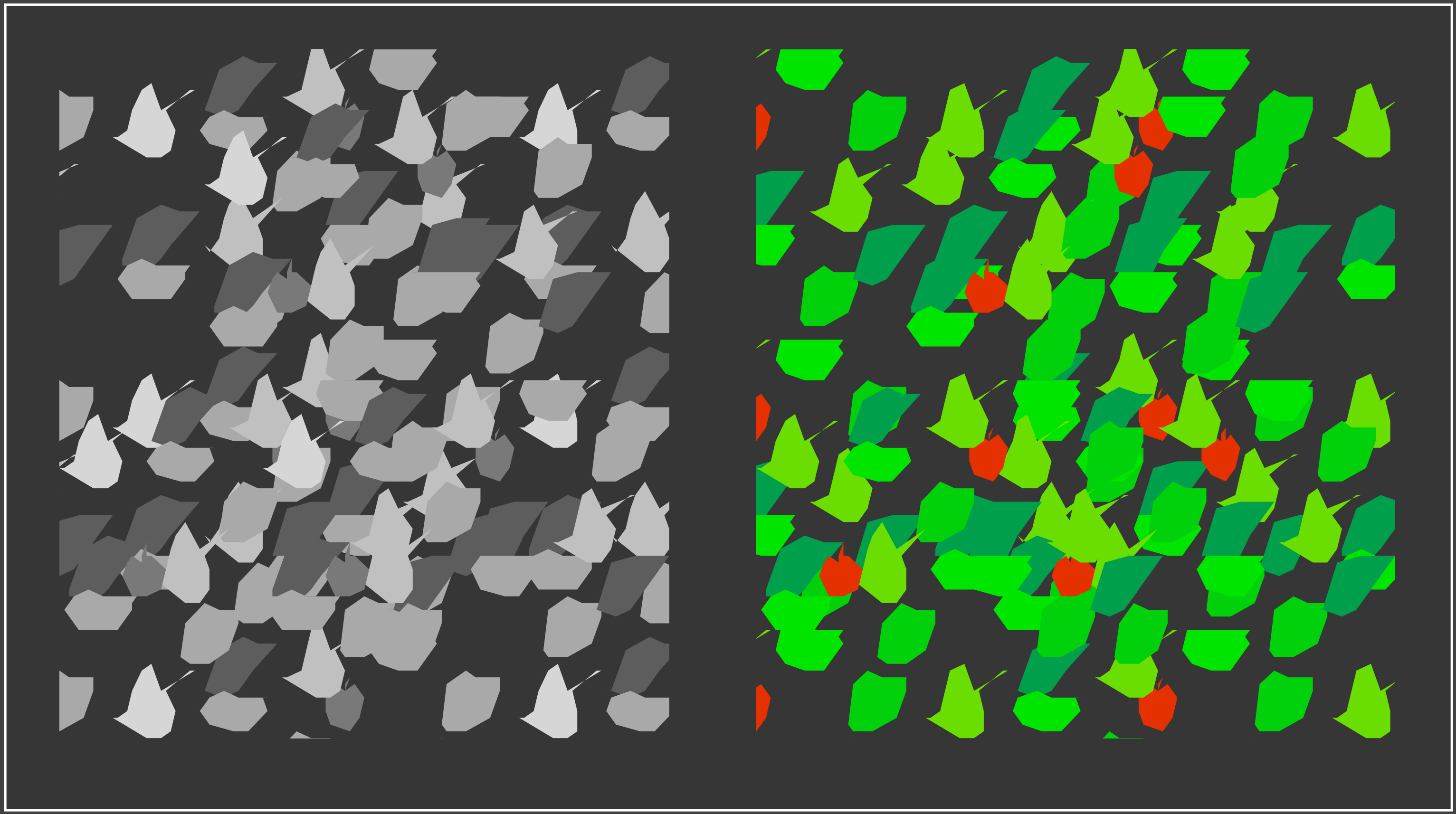






Matthew Conlen University of Washington

# Color in Visualization

Identify, Group, Layer, Highlight



Colin Ware

# Purpose of Color

To label
To measure
To represent and imitate
To enliven and decorate

*"Above all, do no harm."*
- Edward Tufte

# Topics

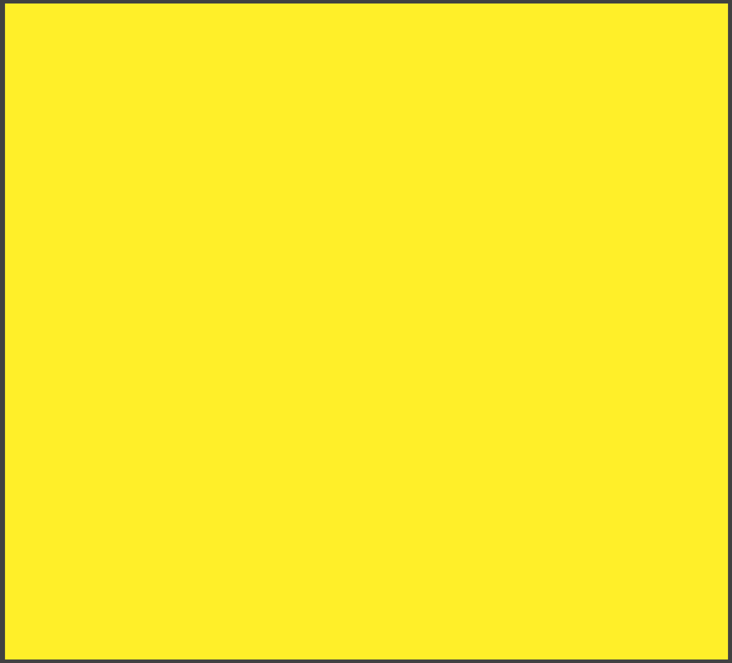
**Perception of Color**
Light, Visual system, Mental models

**Color in Information Visualization**
Categorical & Quantitative encoding
Guidelines for color palette design

# Perception of Color

# What color is this?

# What color is this?



“Yellow”

# What color is this?

# What color is this?

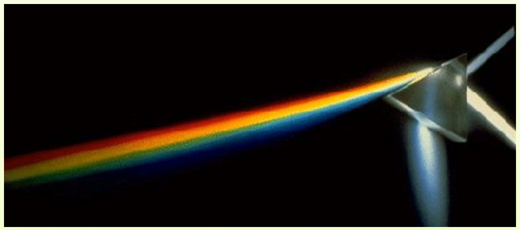
“Blue”

# What color is this?

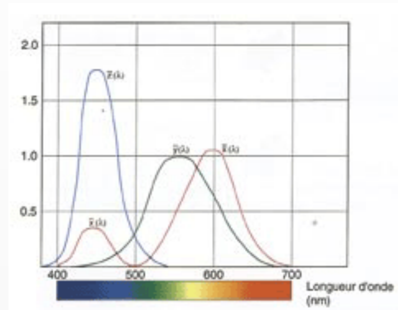
# What color is this?

“Teal” ?

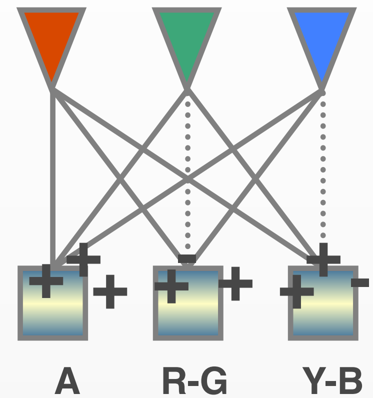
# Perception of Color



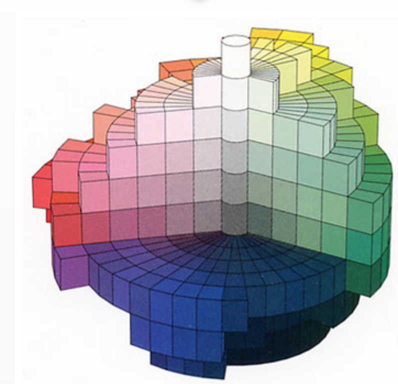
Light



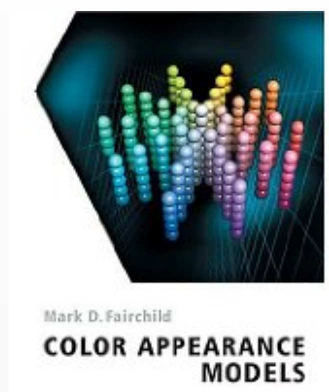

Cone Response




Opponent Signals



Color Perception




Color Appearance

“Yellow”

Color Cognition

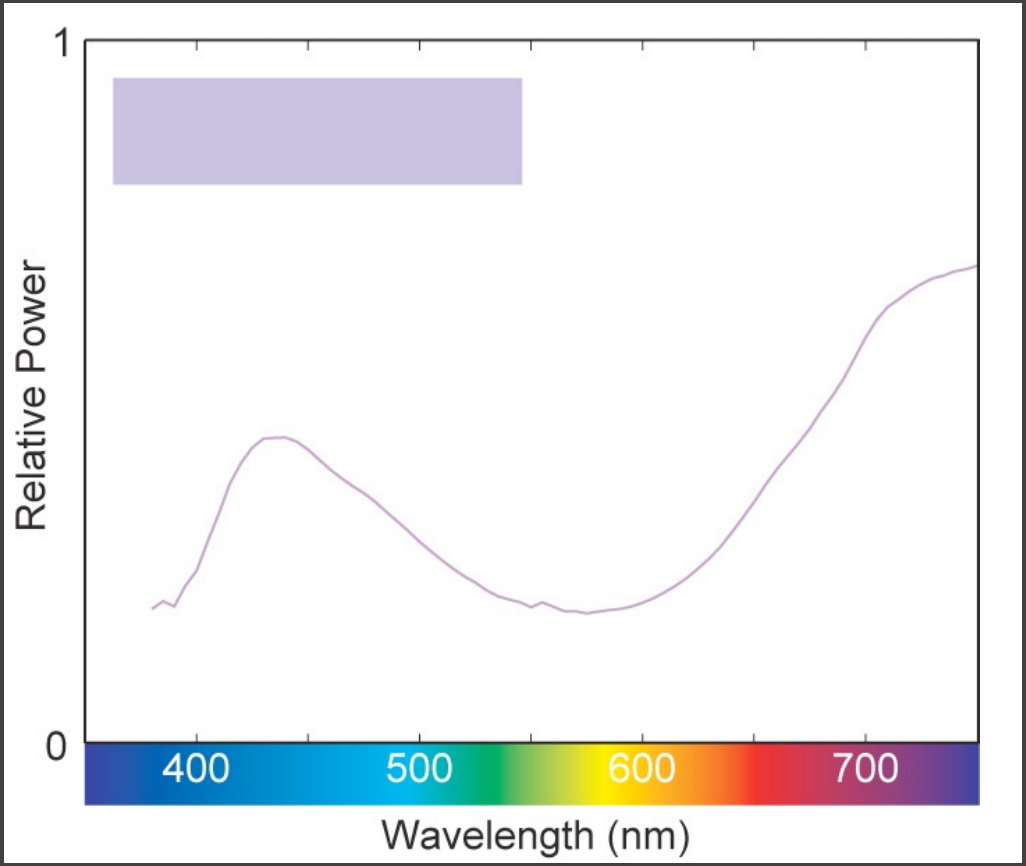
# Physicist’s View

Light as electromagnetic wave

Wavelength

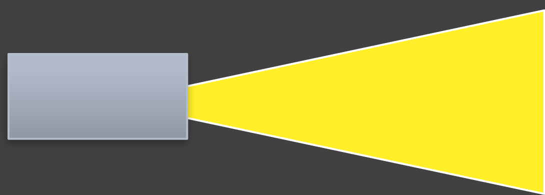
Energy or

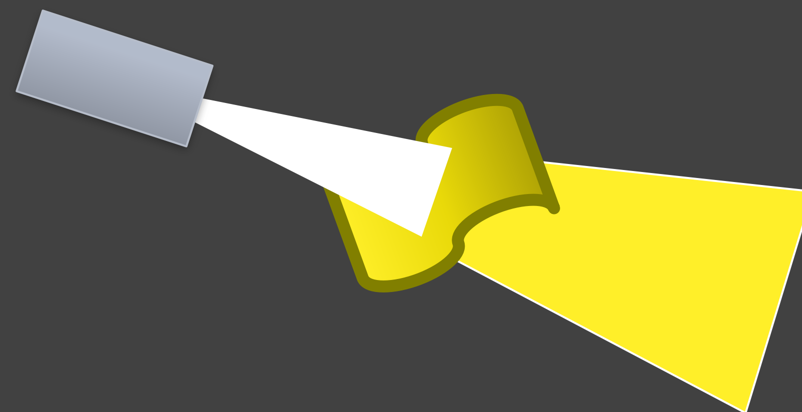
“Relative luminance”



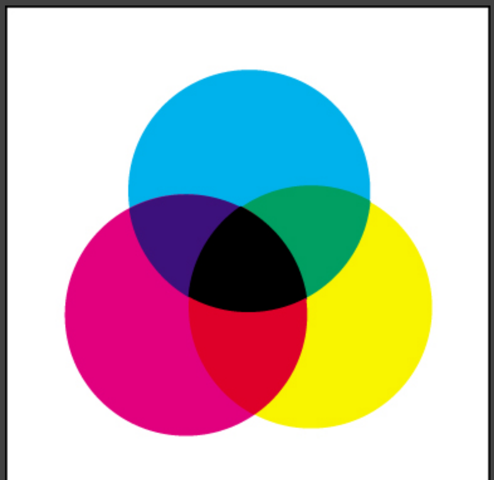

*A Field Guide to Digital Color*, M. Stone

# Emissive vs. Reflective Light



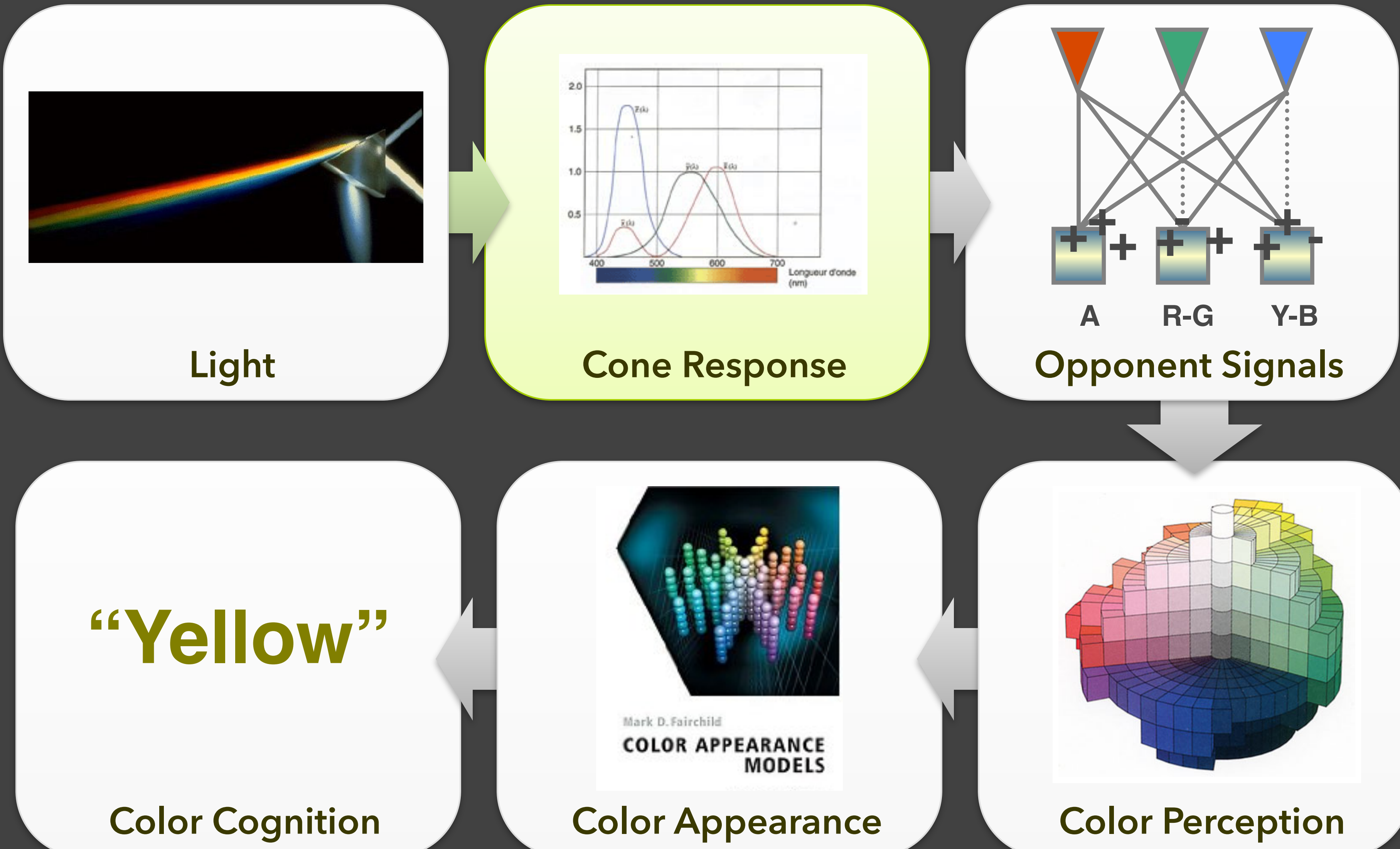


Additive
(digital displays)

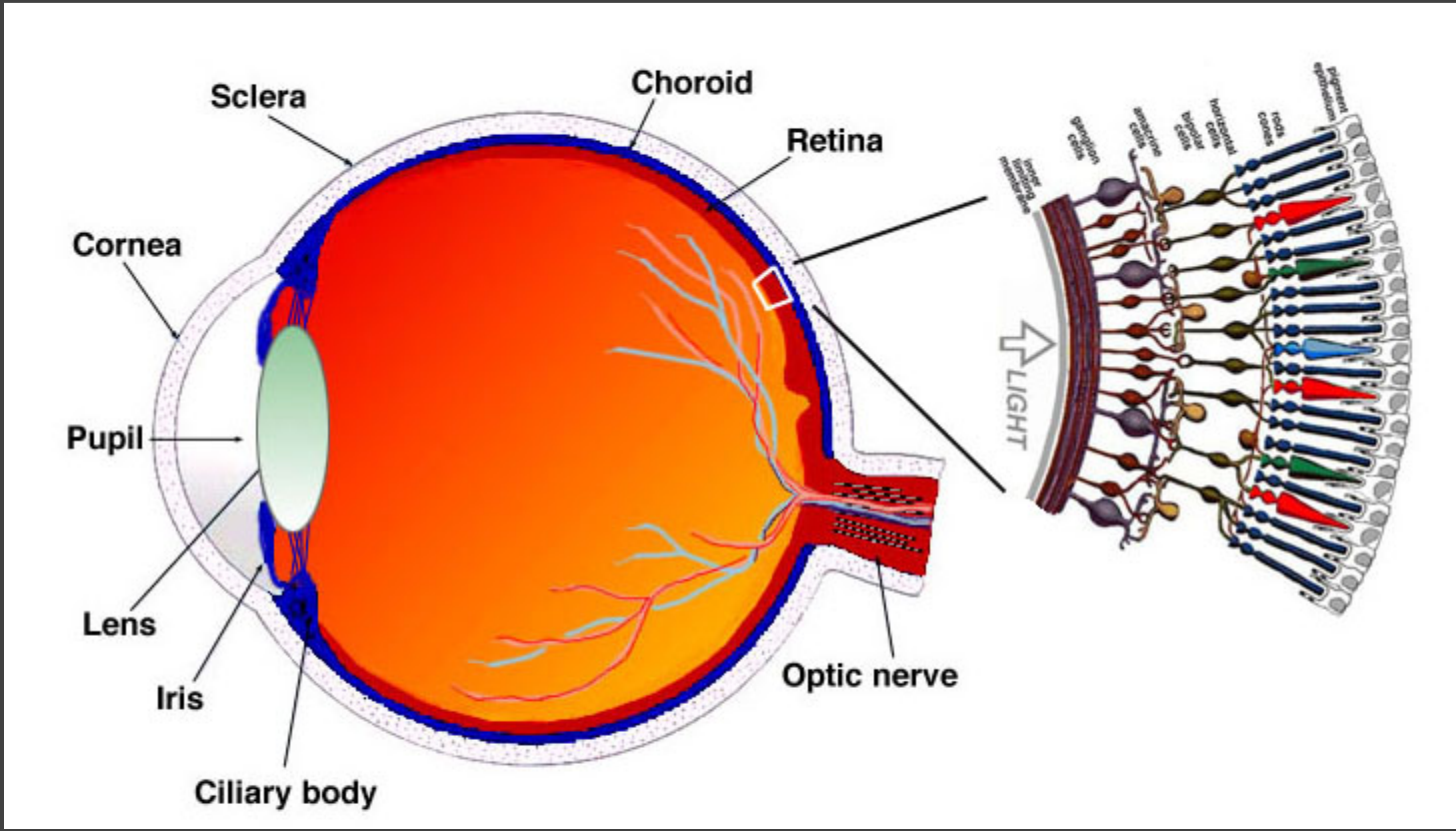


Subtractive
(print, e-paper)

# Perception of Color



# Retina

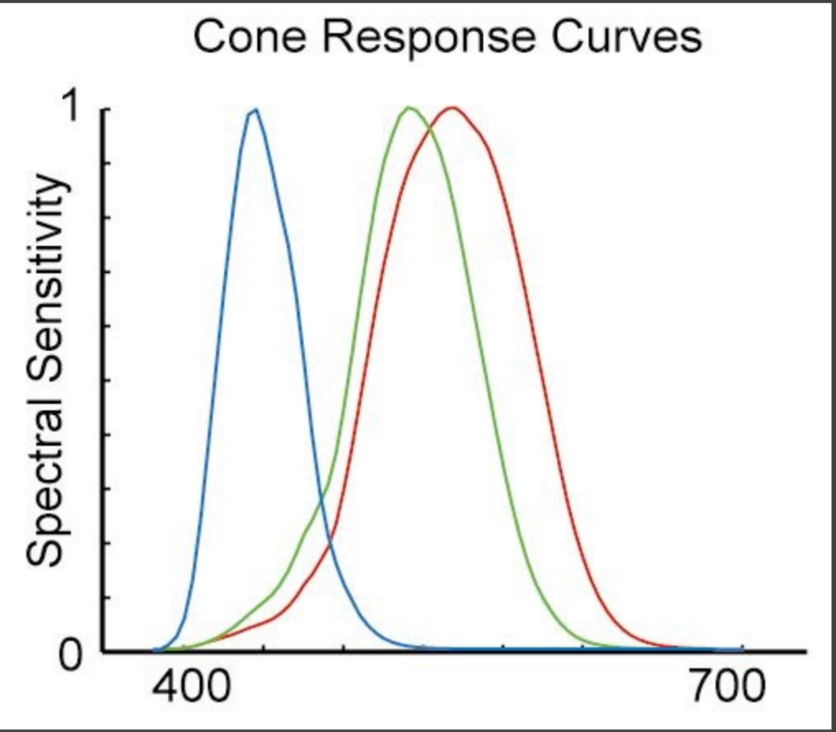



*Simple Anatomy of the Retina*, Helga Kolb

# As light enters our retina…

## LMS (Long, Middle, Short) Cones

Sensitive to different wavelength



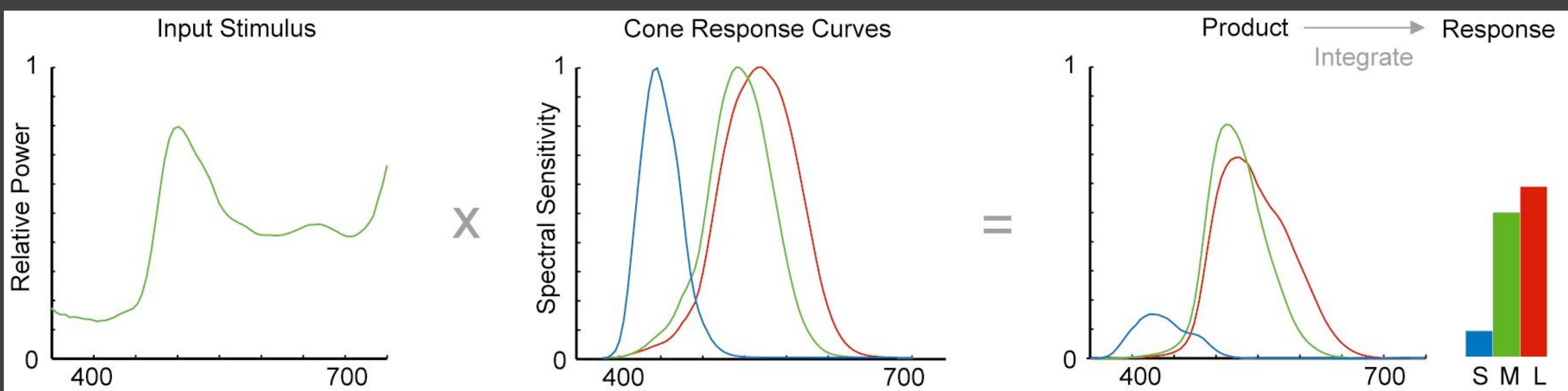

*A Field Guide to Digital Color*, M. Stone

# As light enters our retina…

**LMS (Long, Middle, Short) Cones**

Sensitive to different wavelength

Integration with input stimulus




*A Field Guide to Digital Color*, M. Stone

# Effects of Retina Encoding

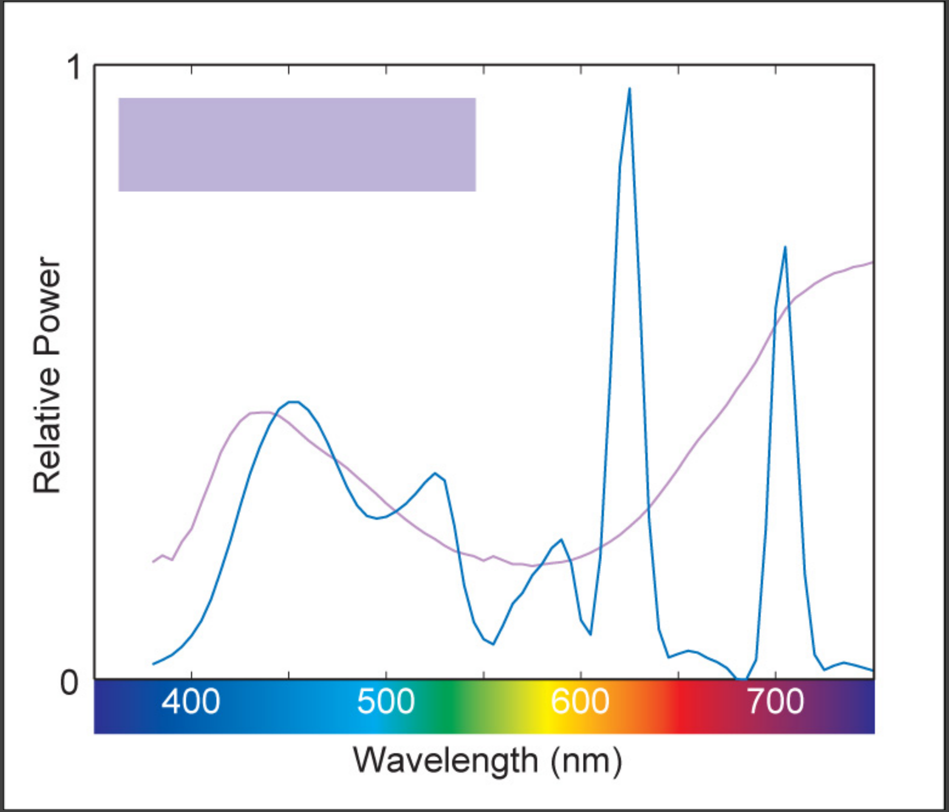
Spectra that stimulate the same LMS response are indistinguishable (a.k.a. "metamers").

**"Tri-stimulus"**

Computer displays

Digital scanners

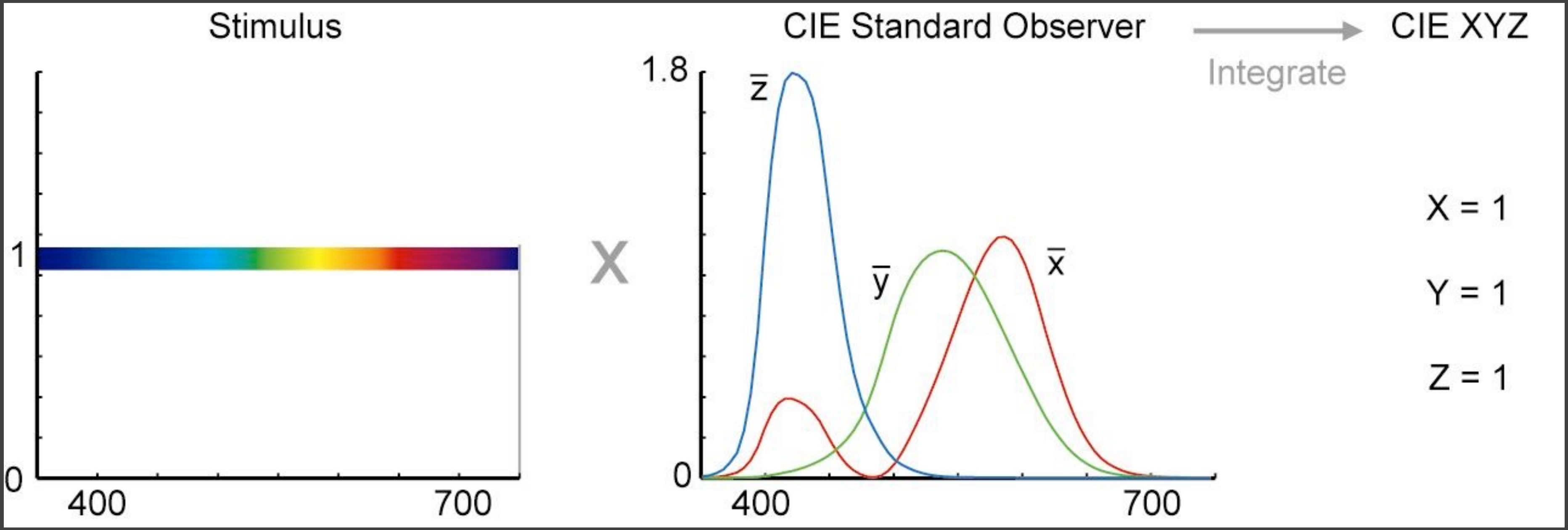
Digital cameras



# CIE XYZ Color Space

Standardized in 1931 to mathematically represent tri-stimulus response.

“Standard observer” response curves

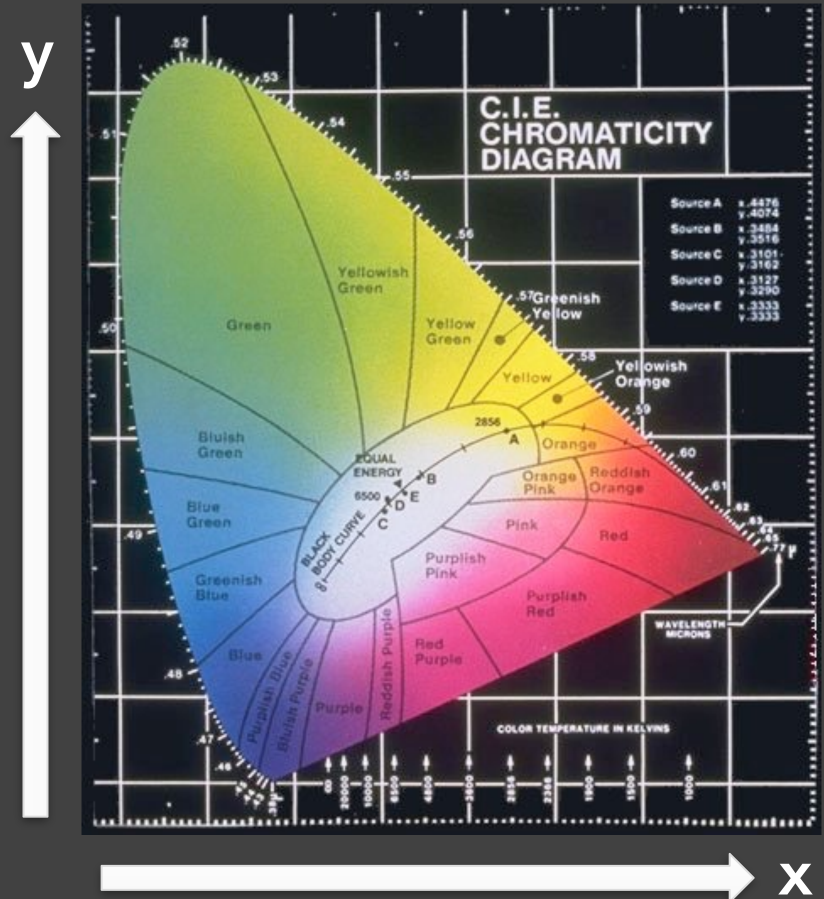


# CIE Chromaticity Diagram

Colorfulness vs. Brightness

$x = X / (X+Y+Z)$

$y = Y / (X+Y+Z)$

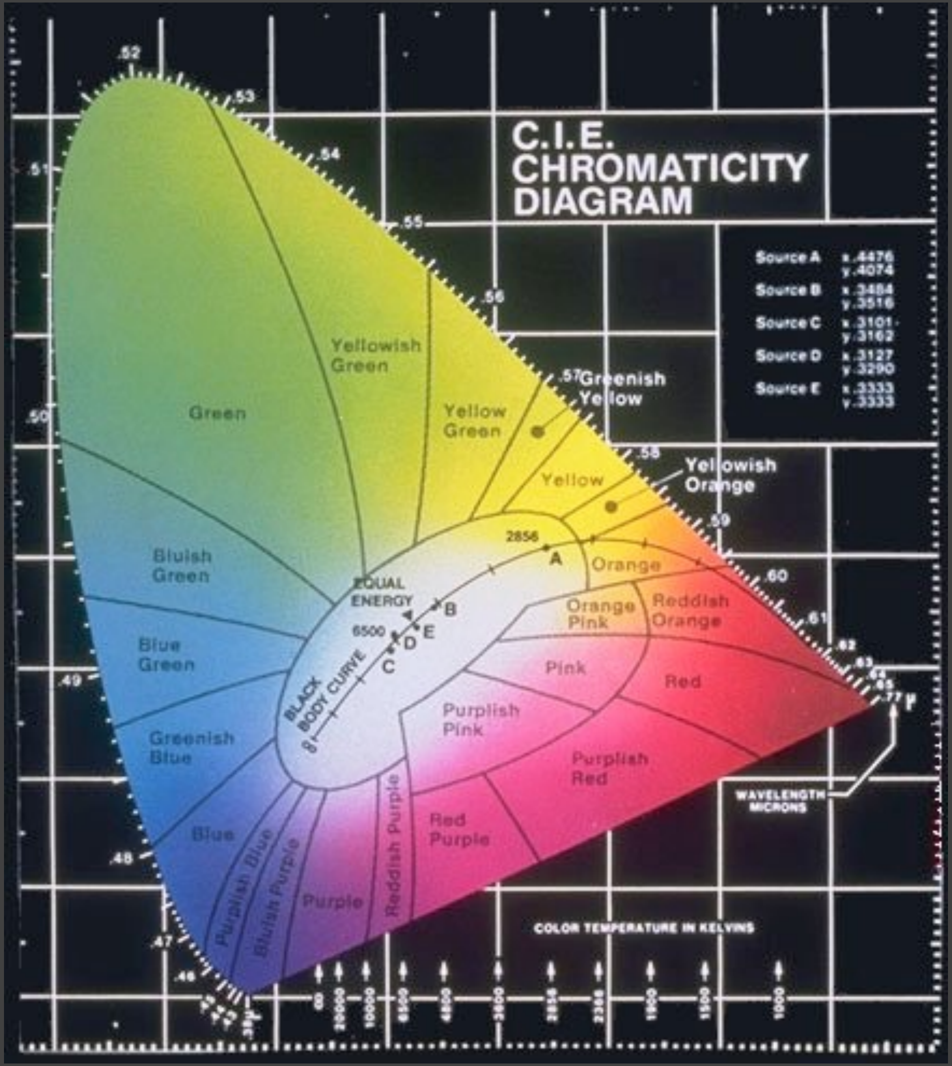


# CIE Chromaticity Diagram

Spectrum locus

Purple line

Mixture of two lights appears as a straight line.



# CIE Chromaticity Diagram

**Spectrum locus**

Purple line

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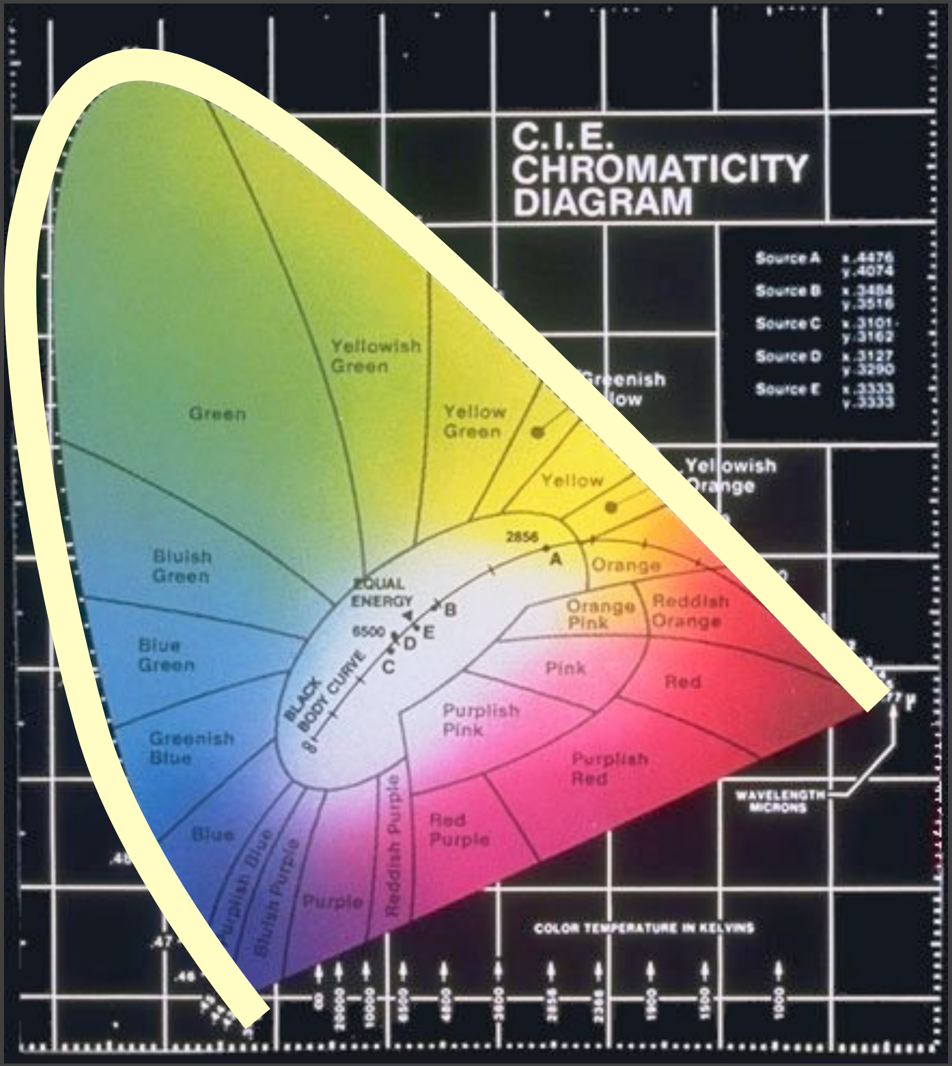

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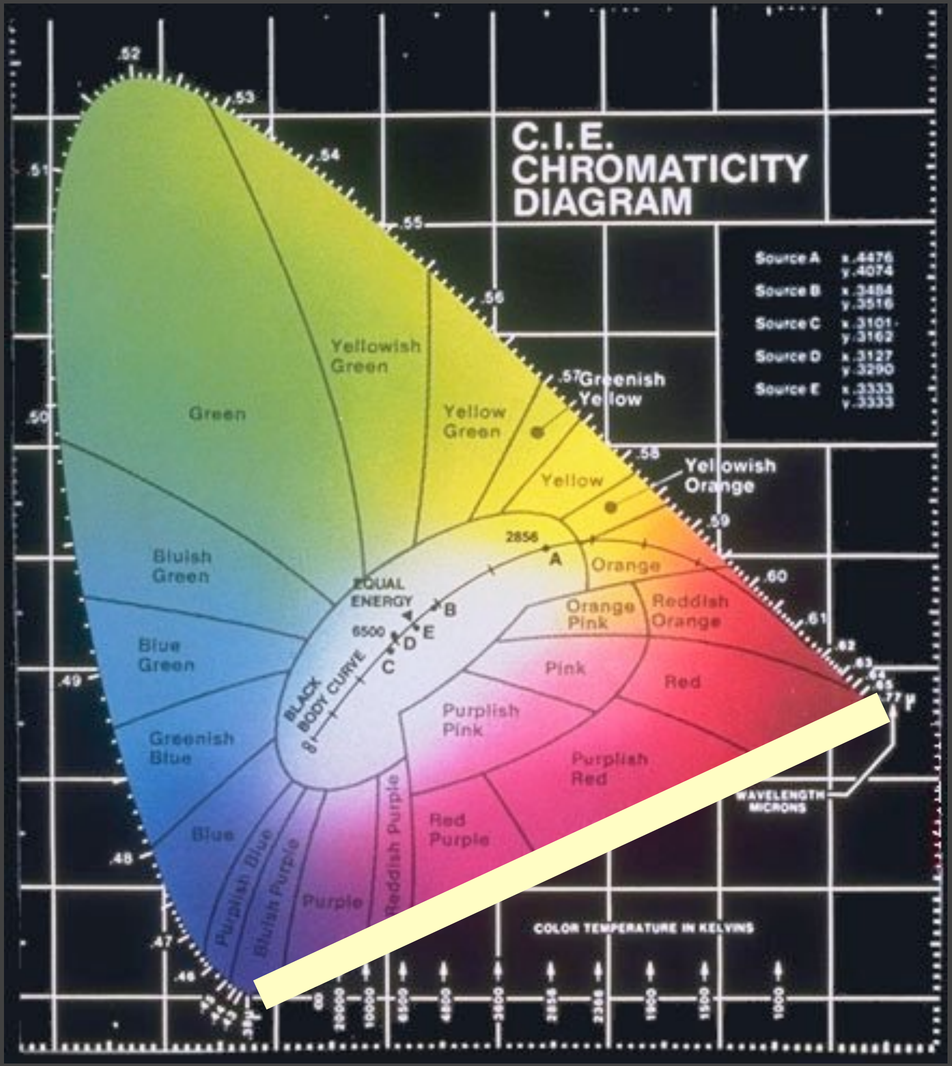

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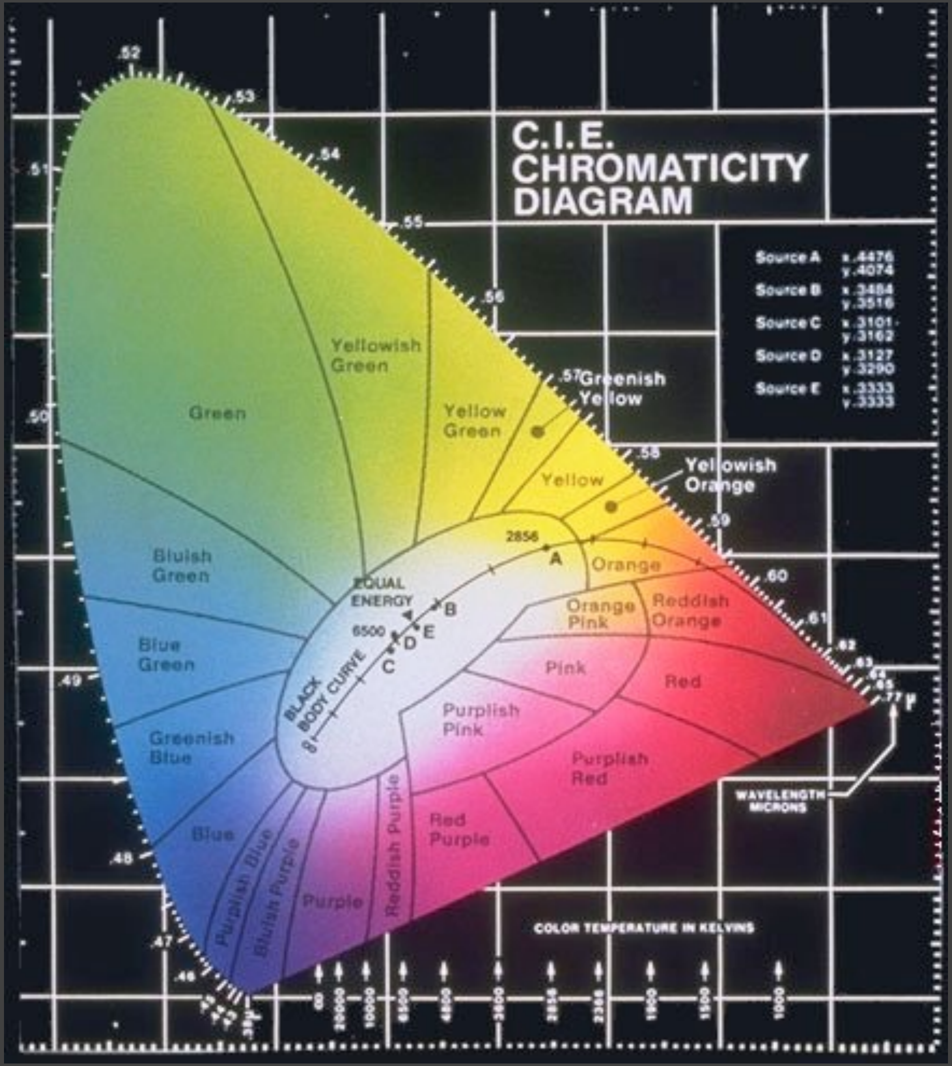
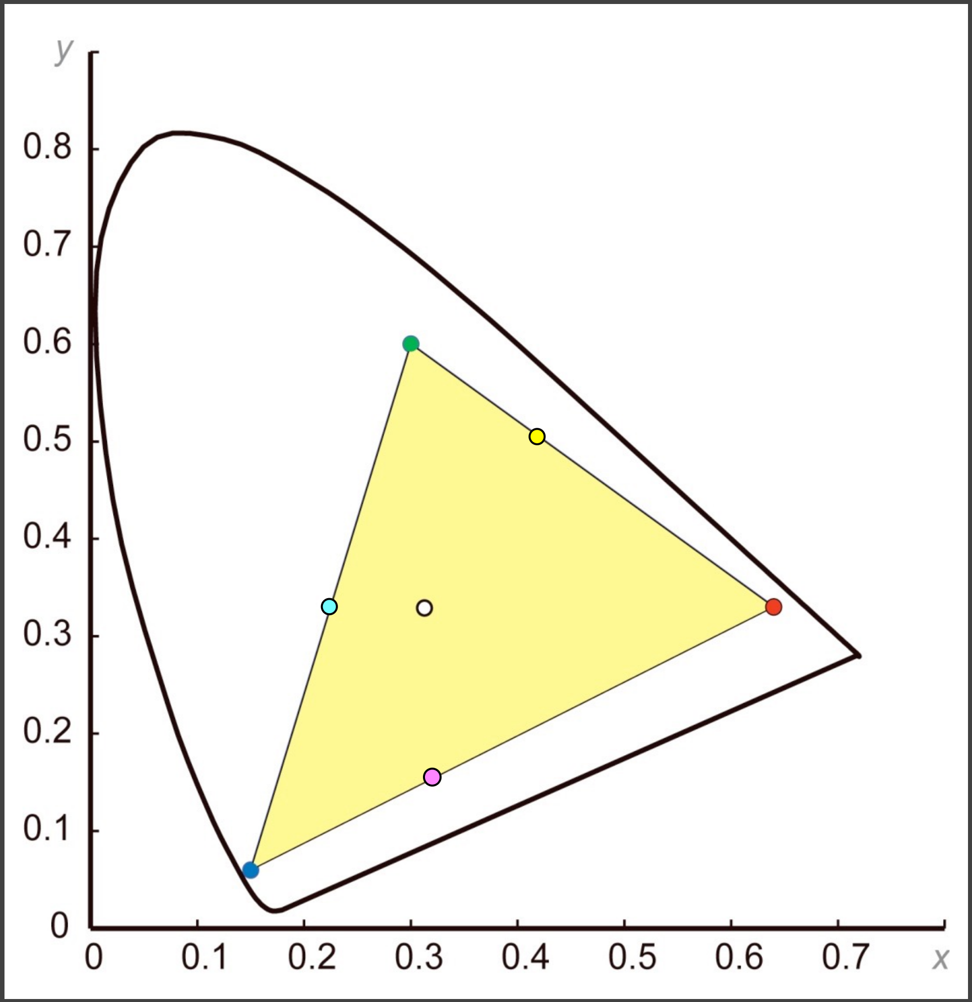


# Display Gamuts

Typically defined by:

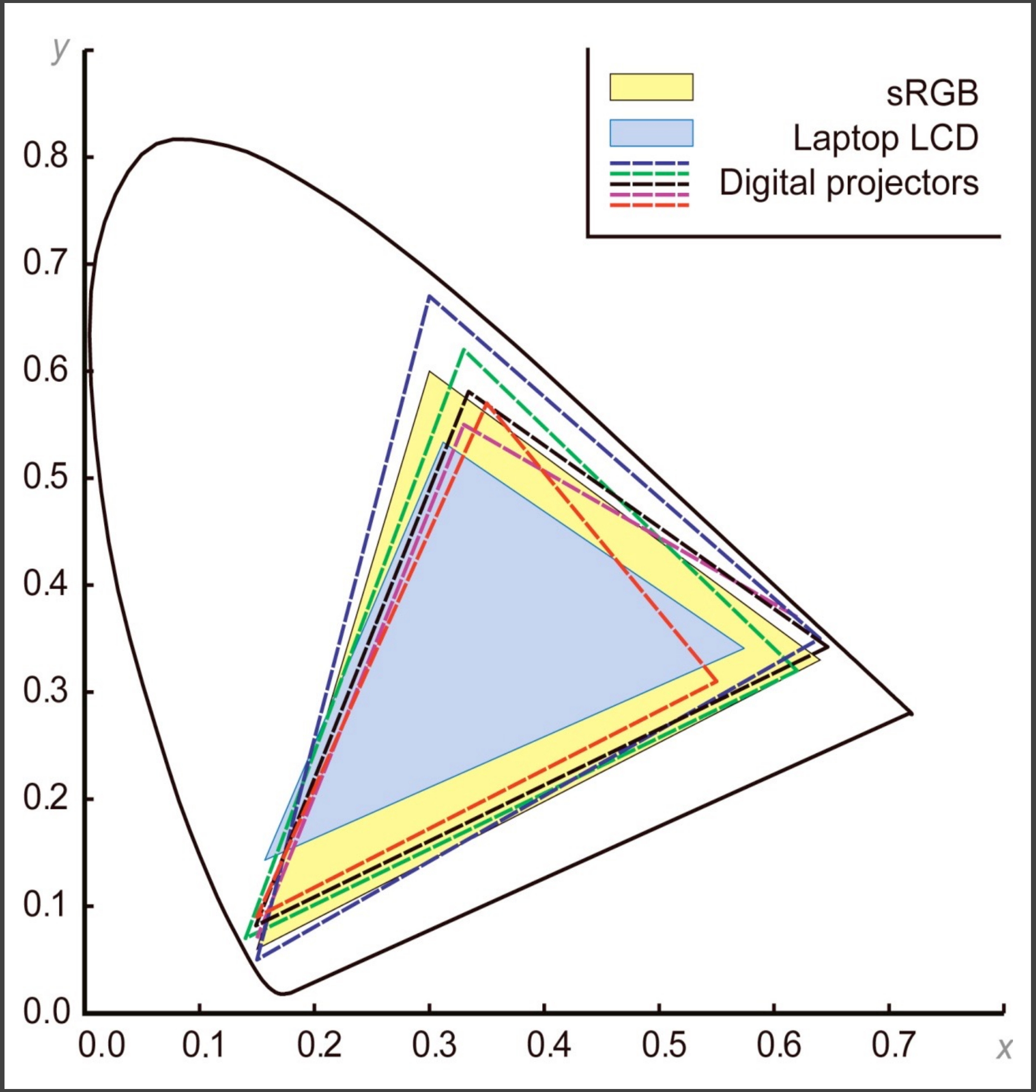
3 Colorants

Convex region



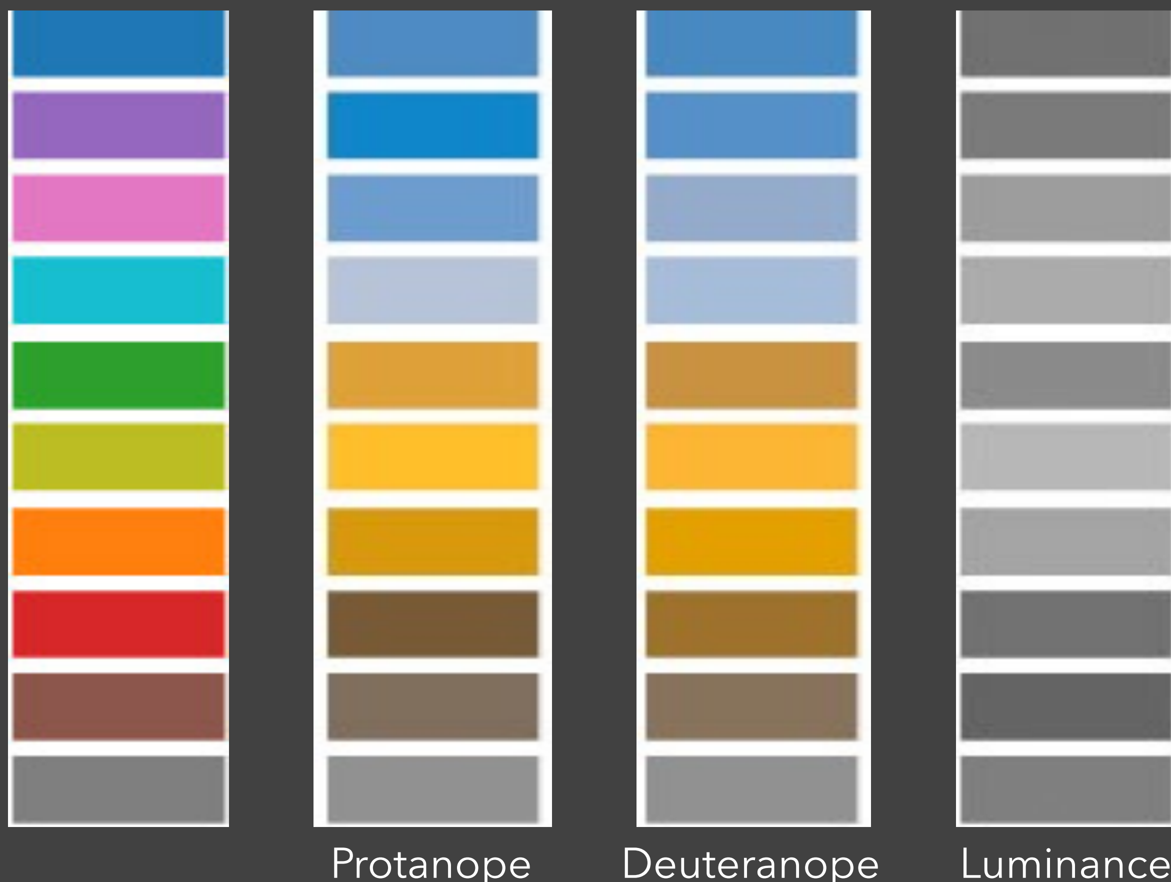
# Display Gamuts

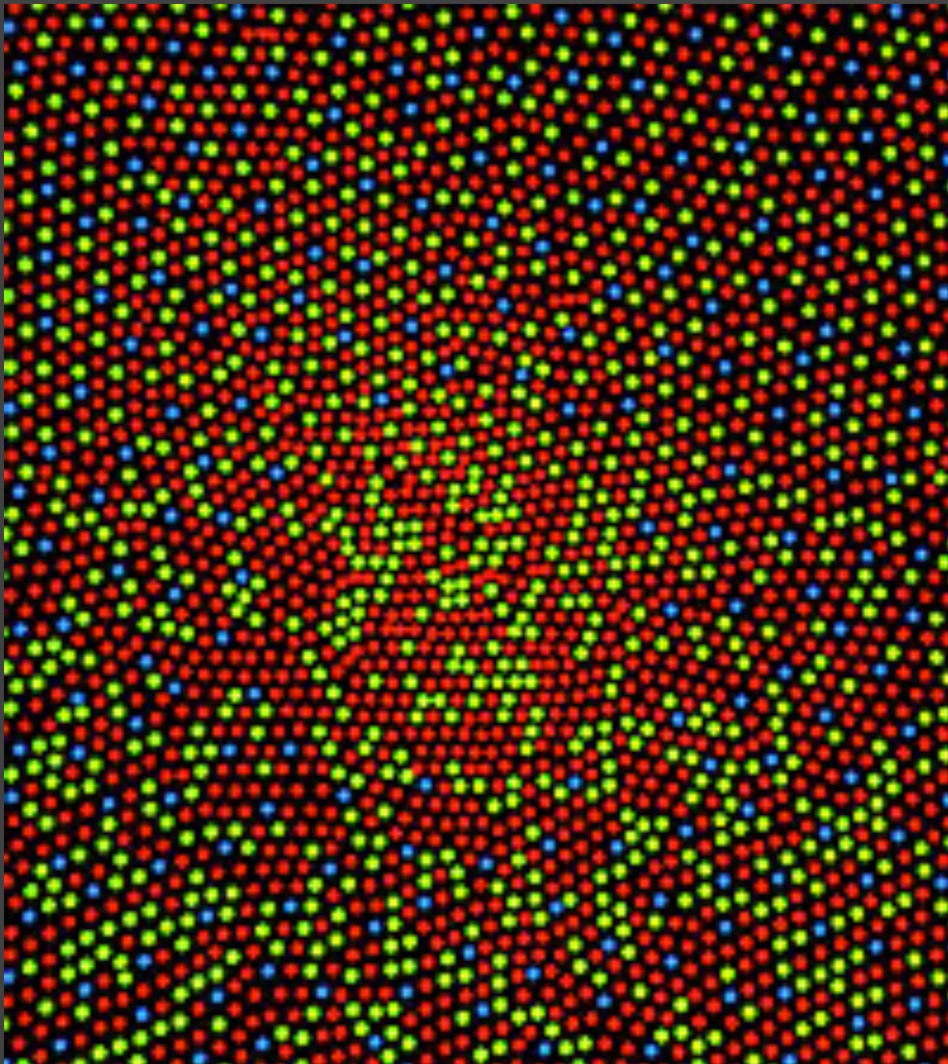
Deviations from sRGB specification



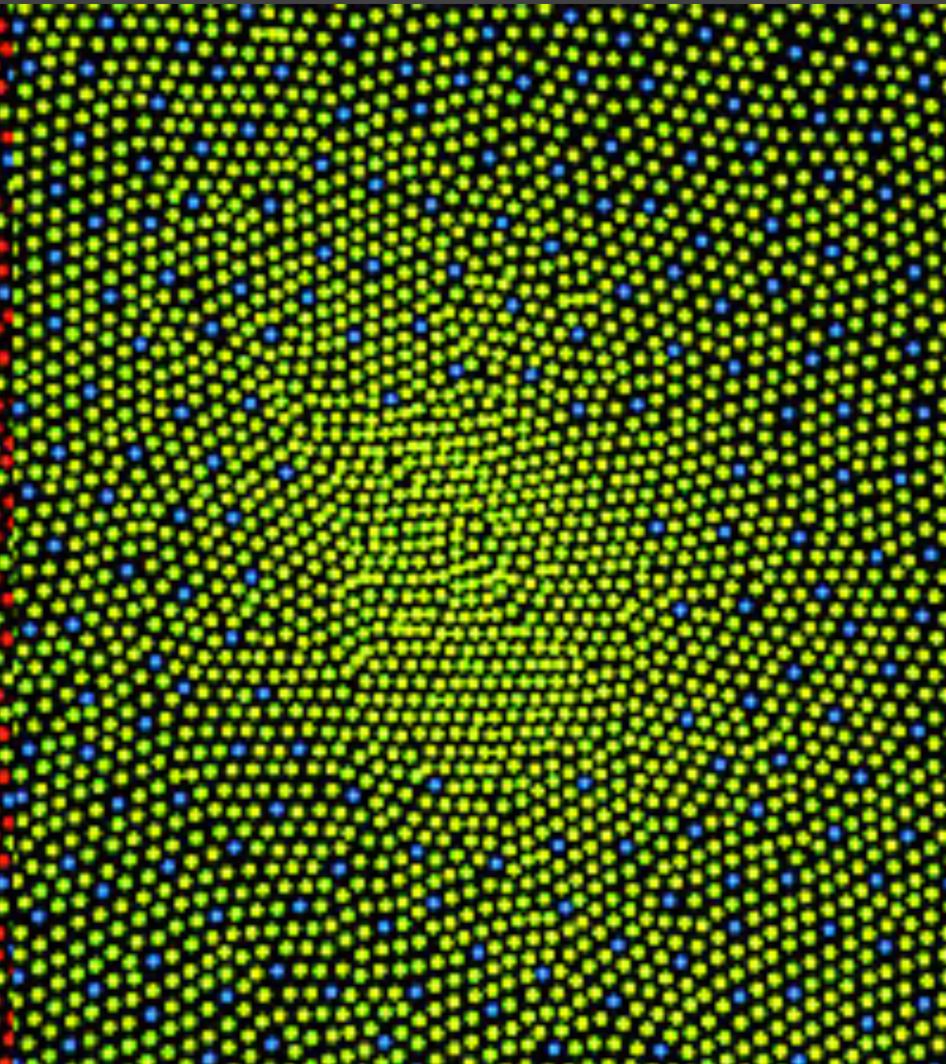
# Color Blindness

Missing one or more cones or rods in retina.





Normal Retina



Protanopia

# Color Blindness Simulators

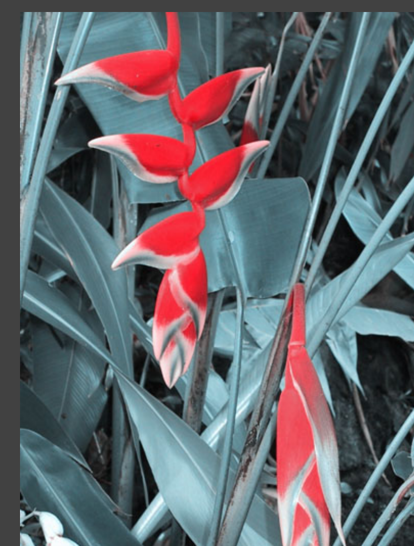
**Simulate color vision deficiencies**

Browser plug-ins (NoCoffee, SEE, …)

Photoshop plug-ins, etc…

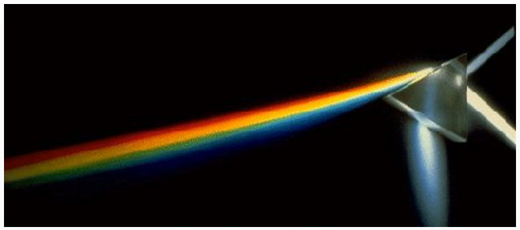
Deuteranope

Protanope

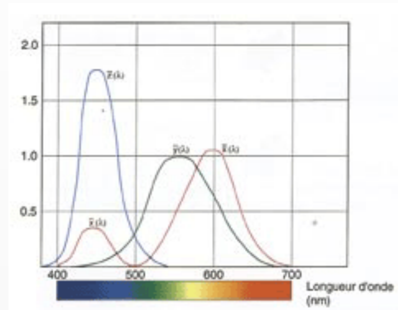


Tritanope

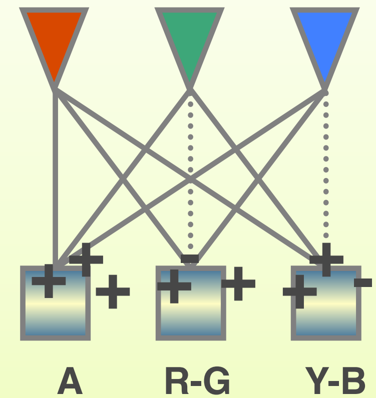
# Perception of Color



Light



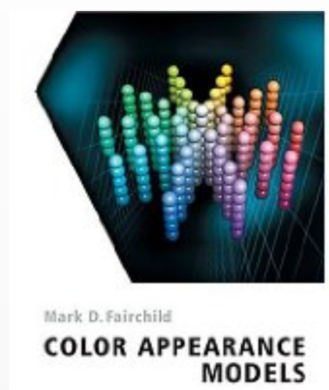

Cone Response



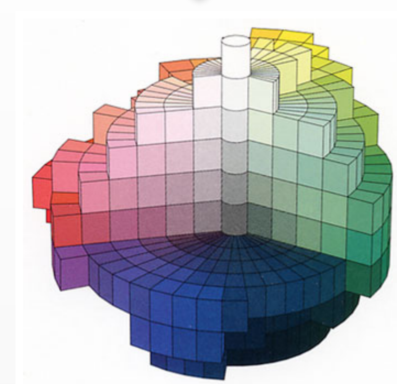

Opponent Signals

“Yellow”

Color Cognition




Color Appearance



Color Perception

# Primary Colors

To paint “all colors”:
Leonardo da Vinci, circa 1500 described in his notebooks a list of simple colors…

**Yellow**
**Blue**
**Green**
**Red**

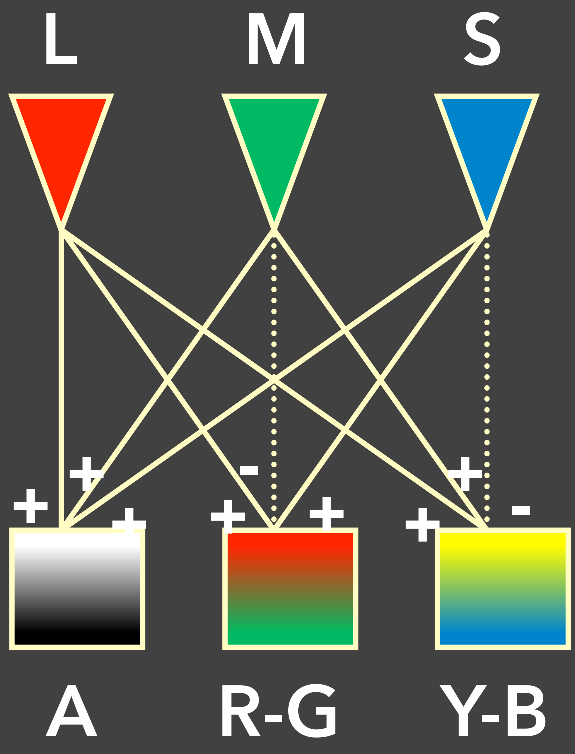
# Opponent Processing

**LMS are combined to create:**

Lightness

Red-green contrast

Yellow-blue contrast



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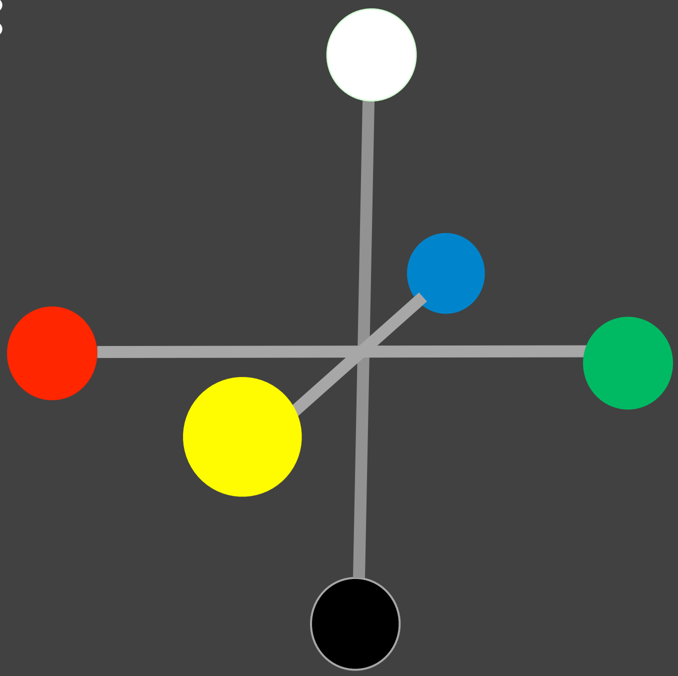

# Opponent Processing

**LMS are combined to create:**

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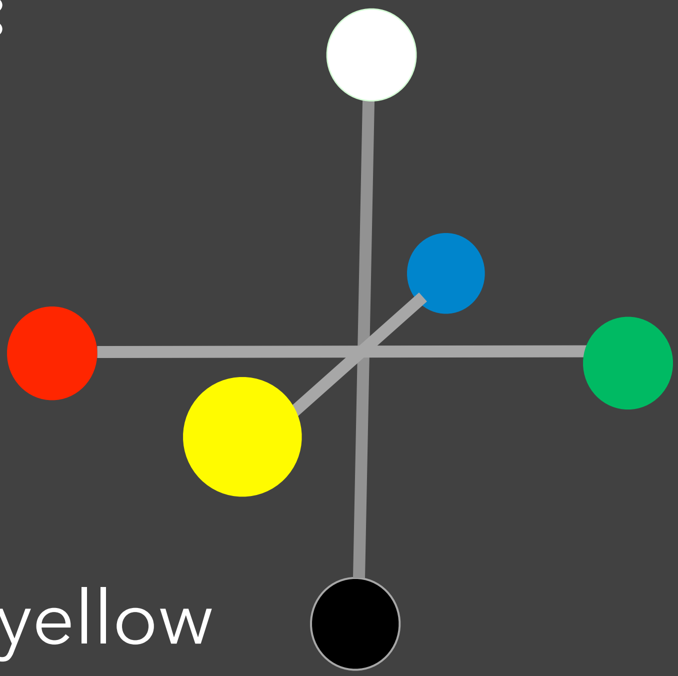


**Experiments**:

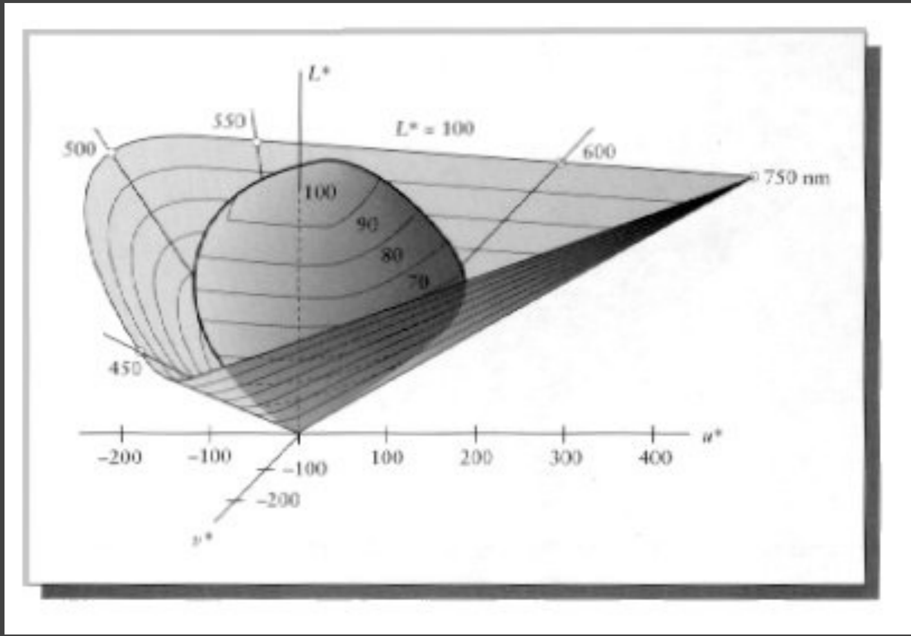
No reddish-green, no blueish-yellow

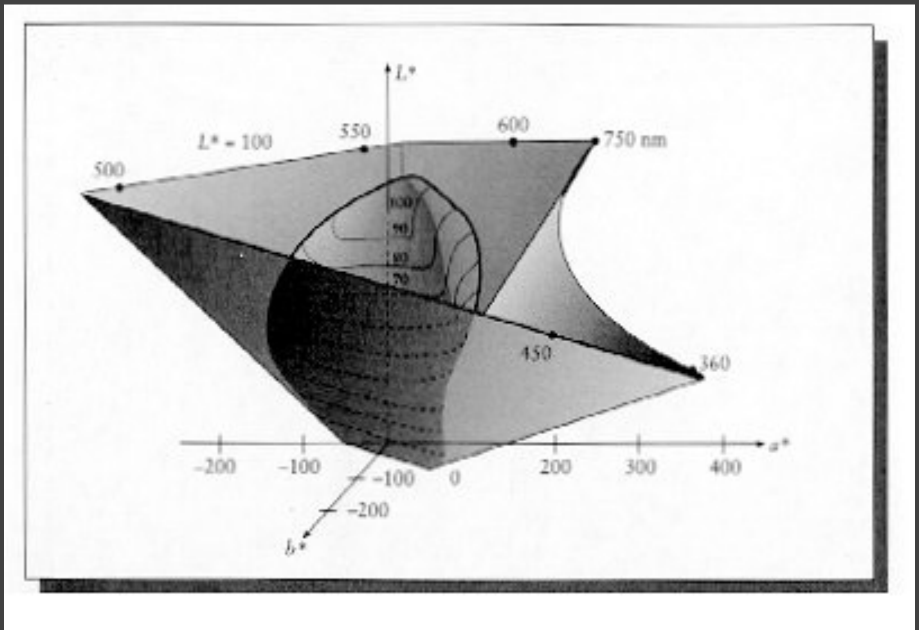
Color after images

# CIE LAB and LUV Color Spaces

Standardized in 1976 to mathematically represent opponent processing theory.

Non-linear transformation of CIE XYZ



# CIE LAB Color Space

Axes correspond to opponent signals

**L*** = Luminance

**a*** = Red-green contrast

**b*** = Yellow-blue contrast

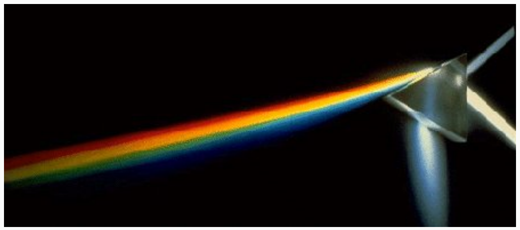
Much more perceptually uniform than sRGB!

Scaling of axes to represent “color distance”

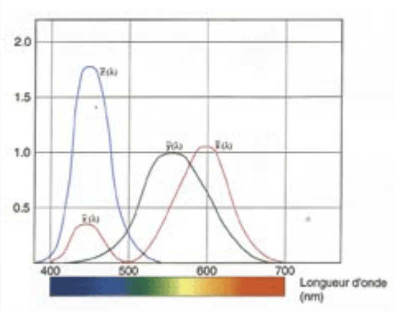
JND = Just noticeable difference (~2.3 units)

D3 includes LAB color space support!

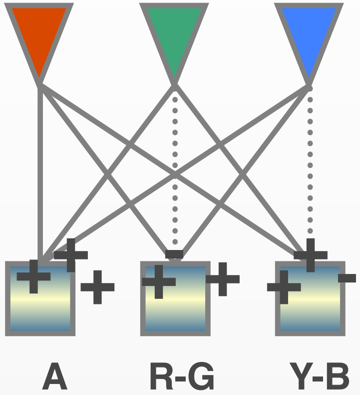
# Perception of Color



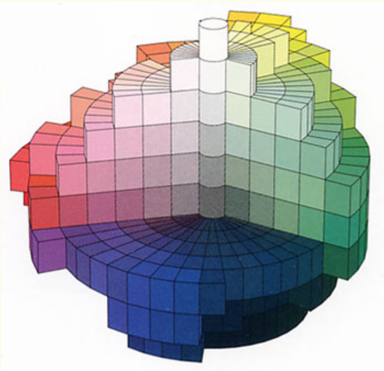
Light



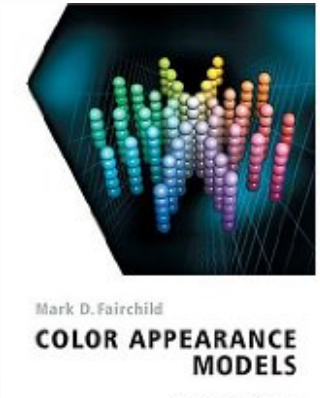

Cone Response




Opponent Signals



Color Perception




Color Appearance

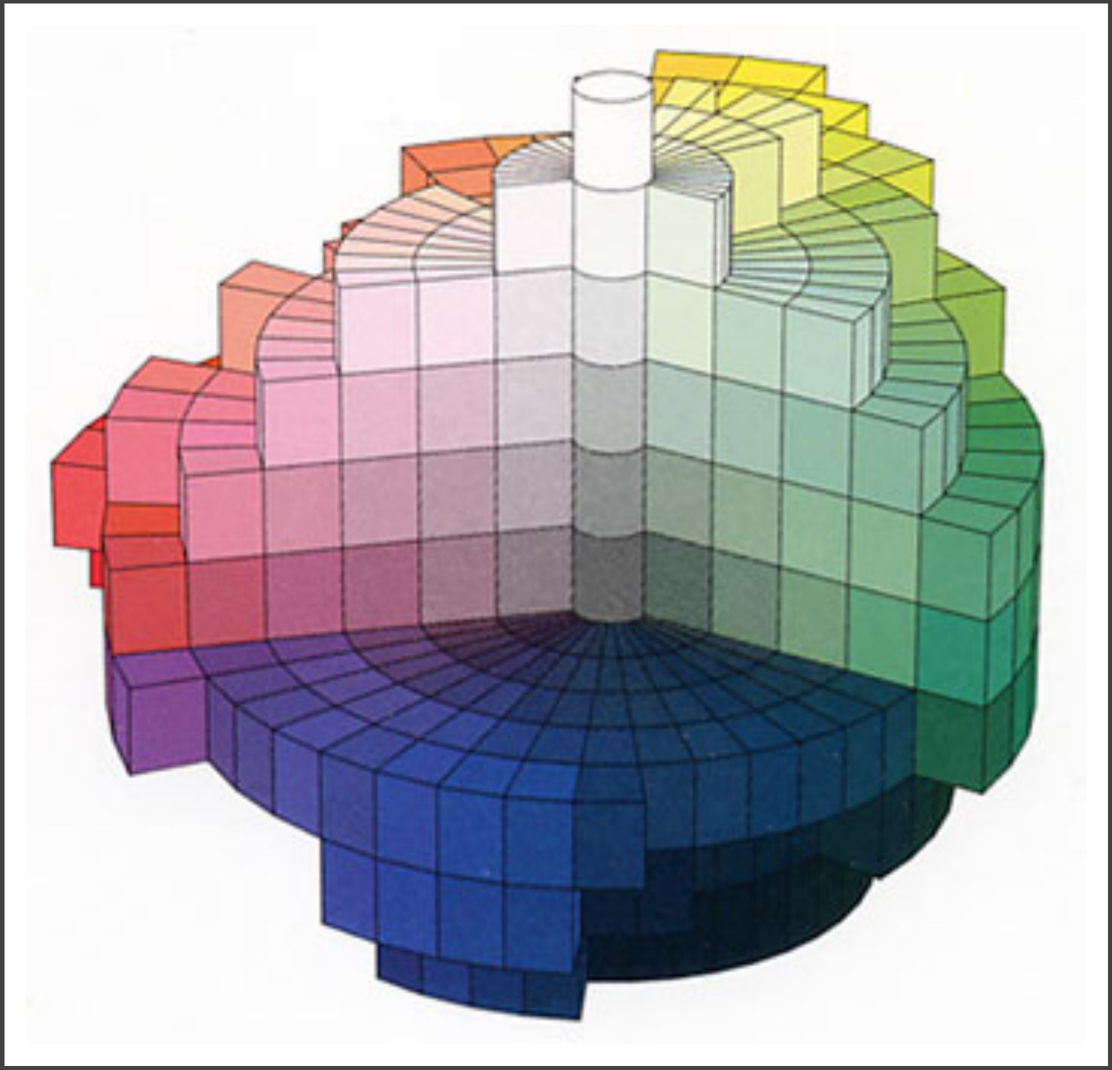
**“Yellow”**

Color Cognition

# Albert Munsell

Developed the first perceptual color system based on his experience as an artist (1905).

# Hue, Value and Chroma



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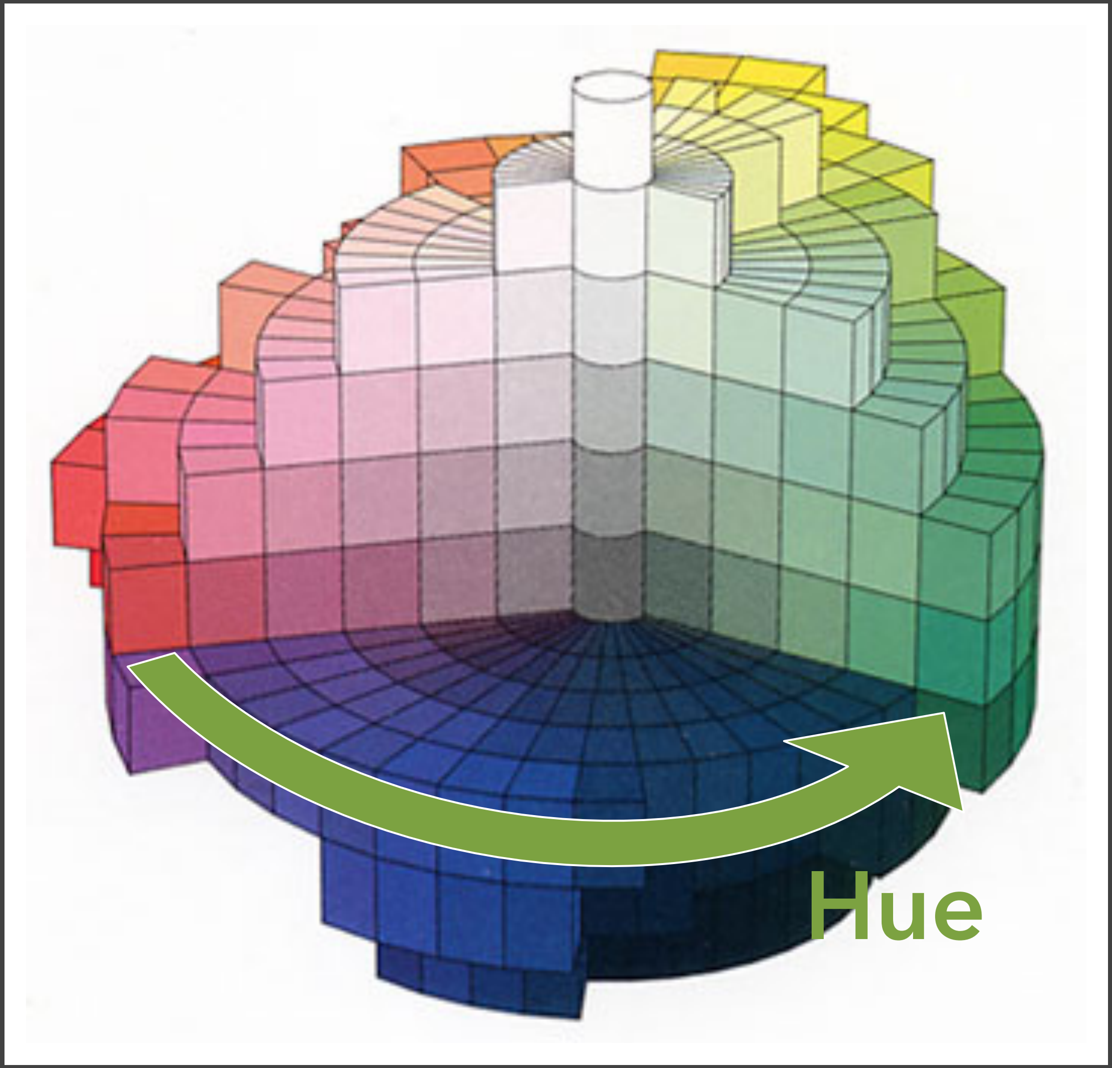

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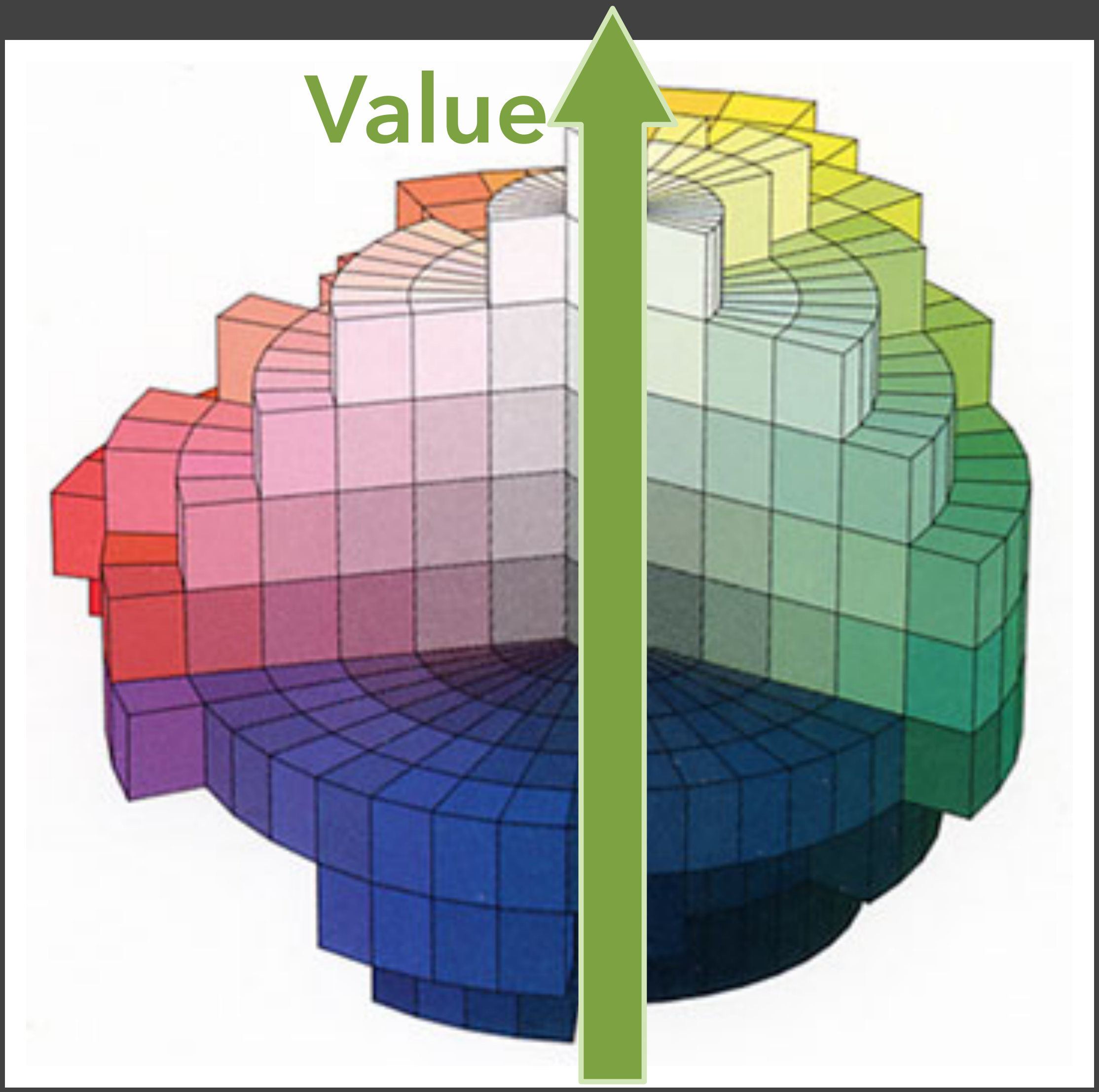

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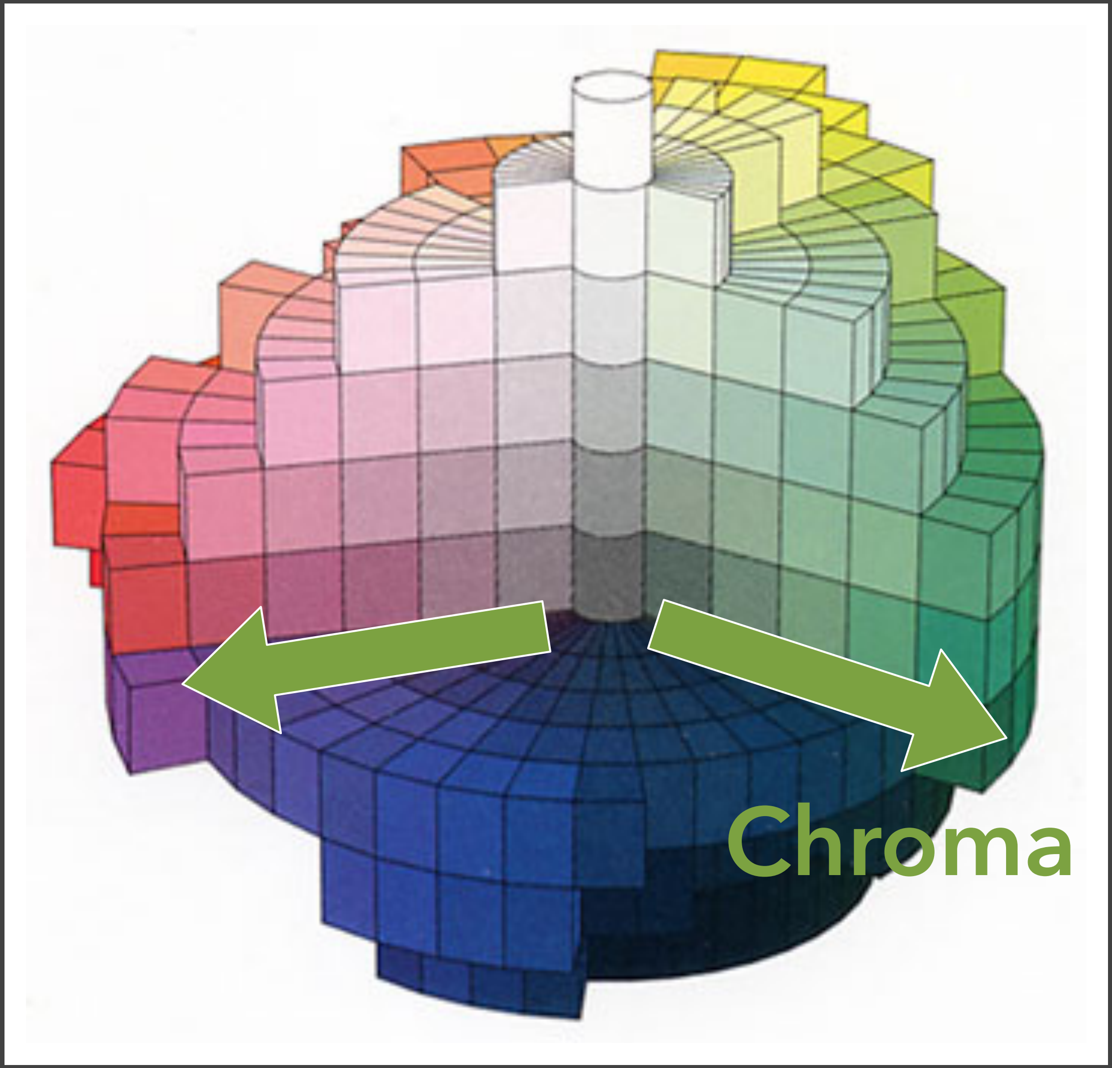


# Munsell Color System

Perceptually-based

Precisely reference a color

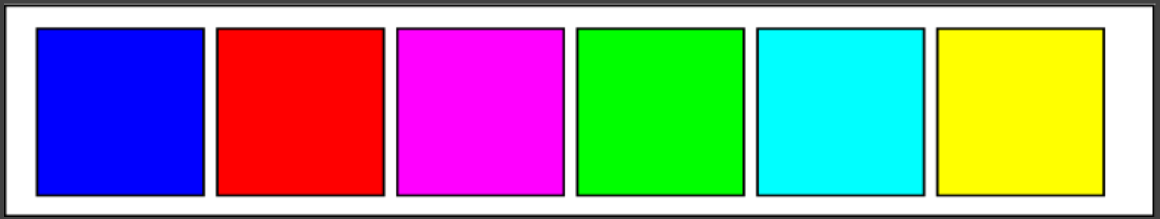
Intuitive dimensions

Look-up table (LUT)

# Munsell Color System

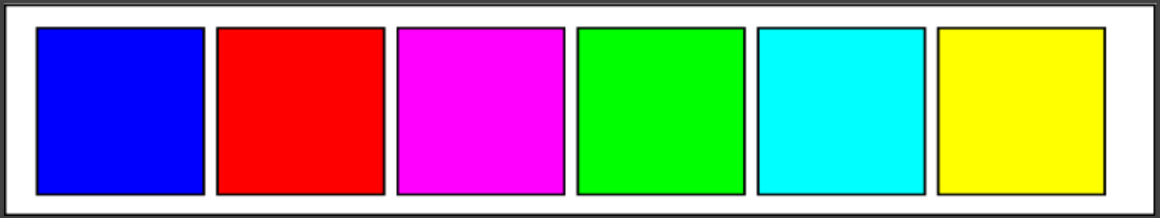
# Perceptual Brightness

Color palette



# Perceptual Brightness

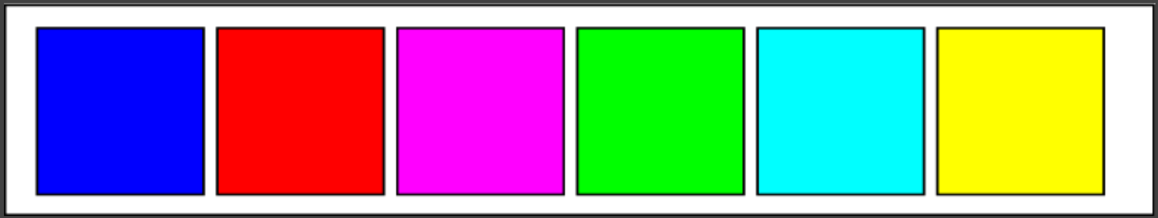
Color palette



HSL Lightness
*(Photoshop)*

# Perceptual Brightness

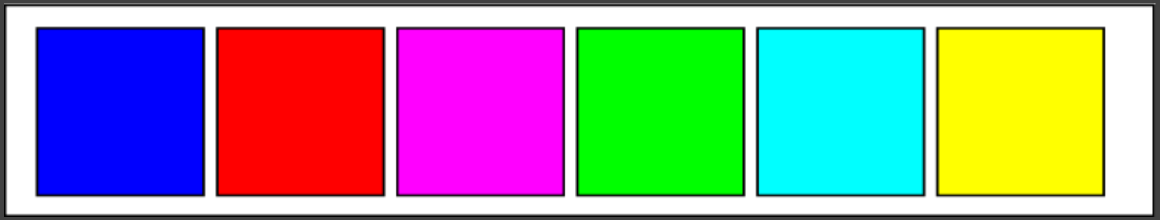
Color palette



Luminance Y
*(CIE XYZ)*

# Perceptual Brightness

Color palette



Munsell Value

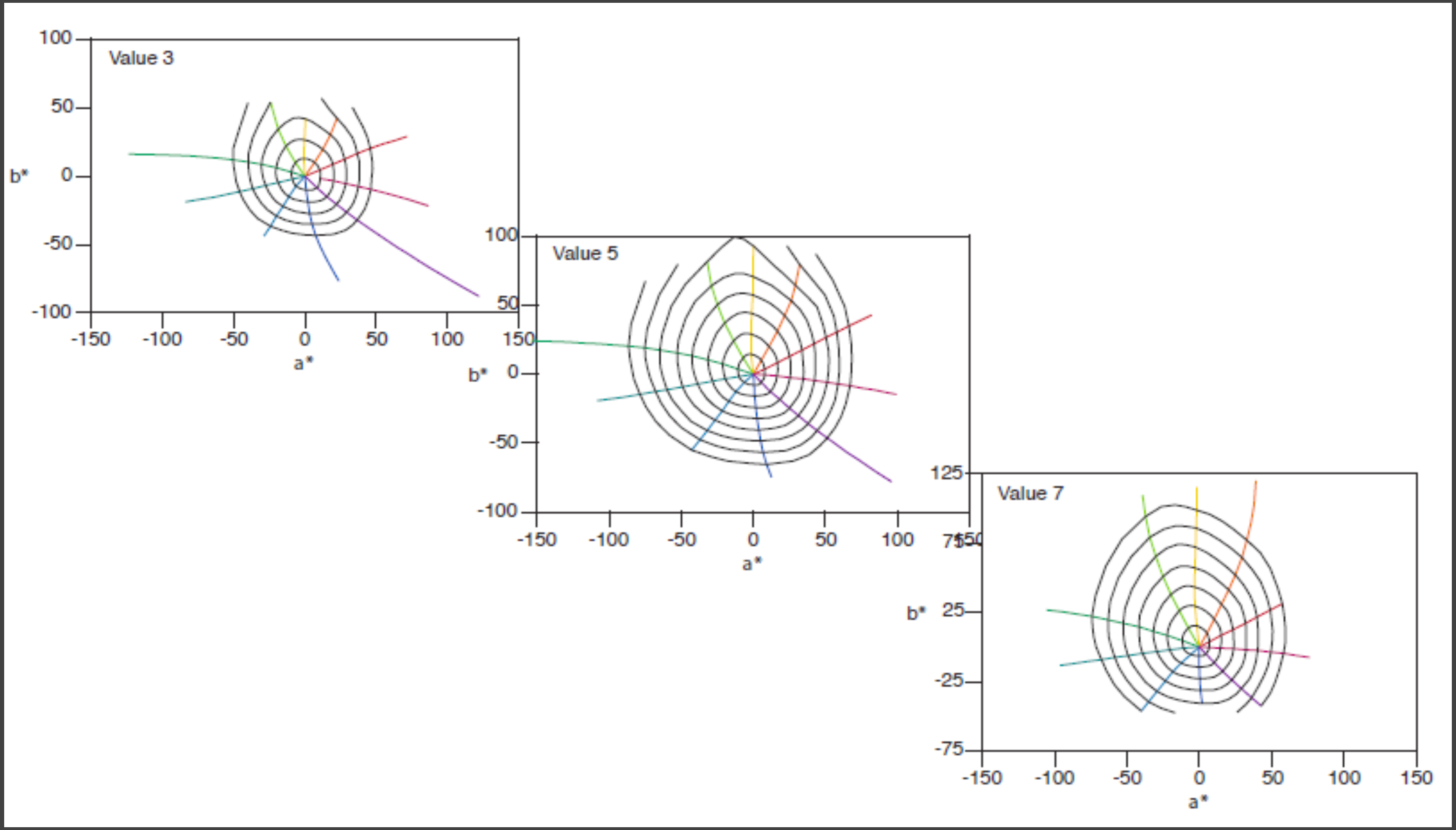
# Perceptual Brightness

Color palette

Munsell Value
L* (CIE LAB)

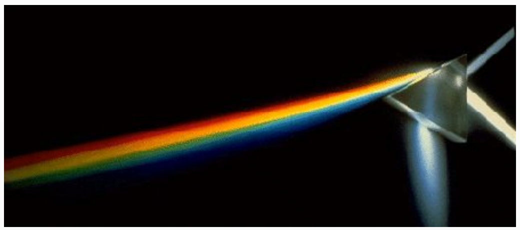
# Perceptually-Uniform Color Space

## Munsell colors in CIE LAB coordinates

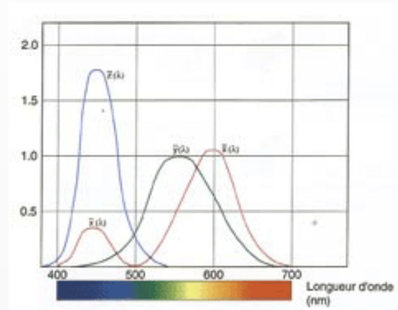



Mark Fairchild

# Perception of Color



Light

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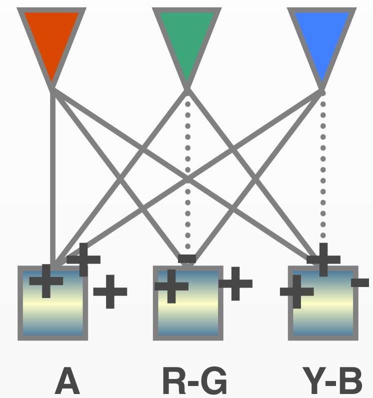
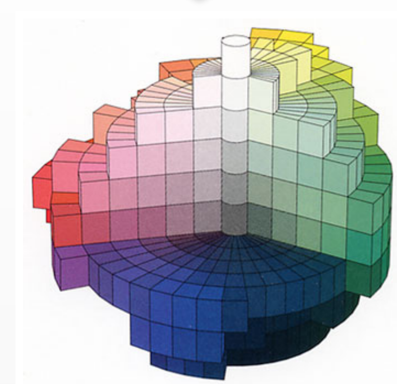
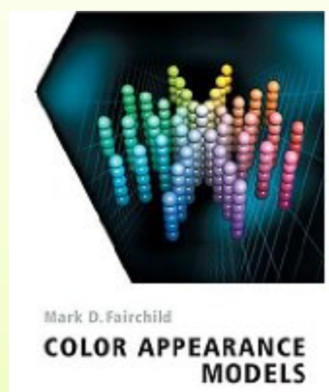



Opponent Signals



Color Perception




Color Appearance

“Yellow”

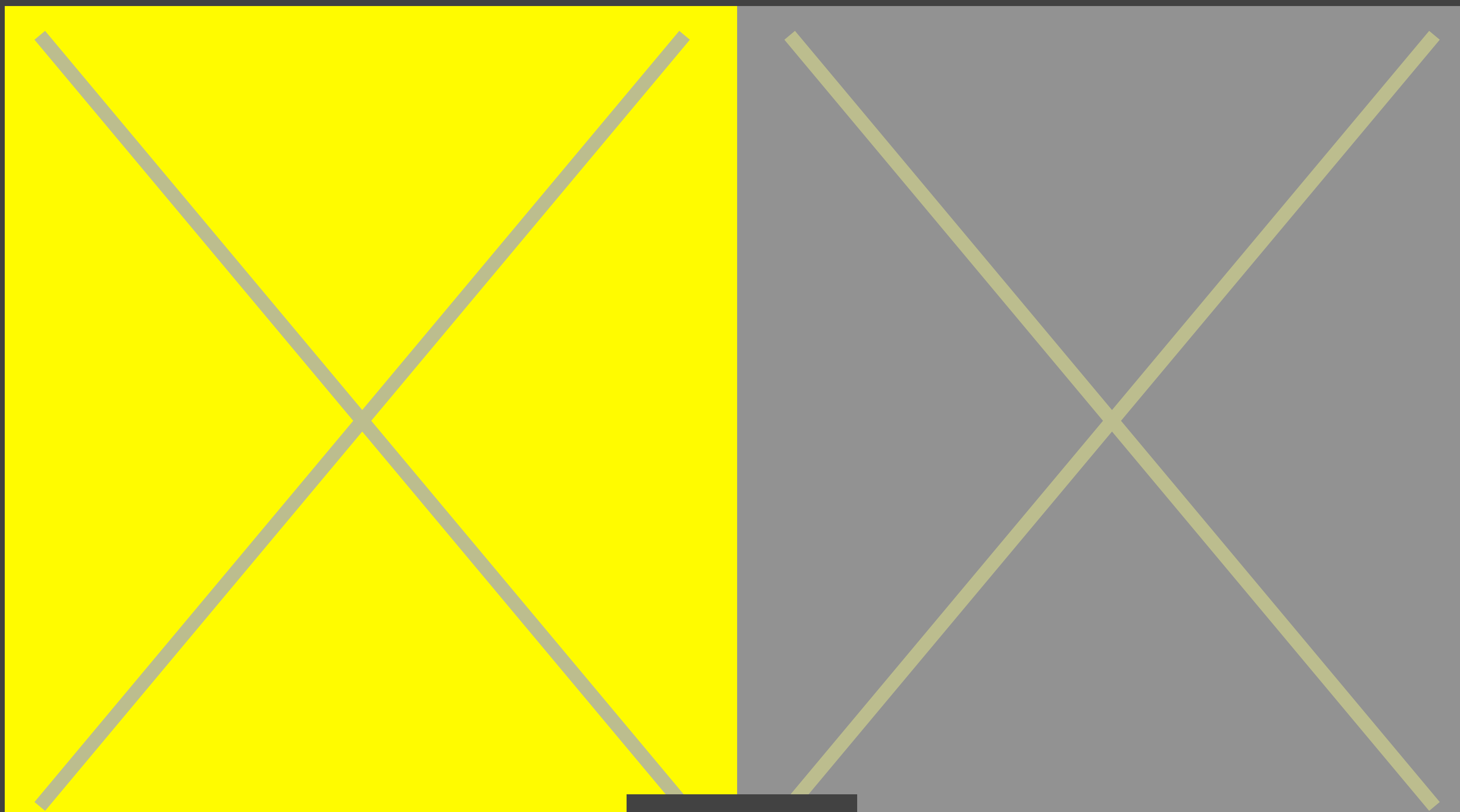
Color Cognition

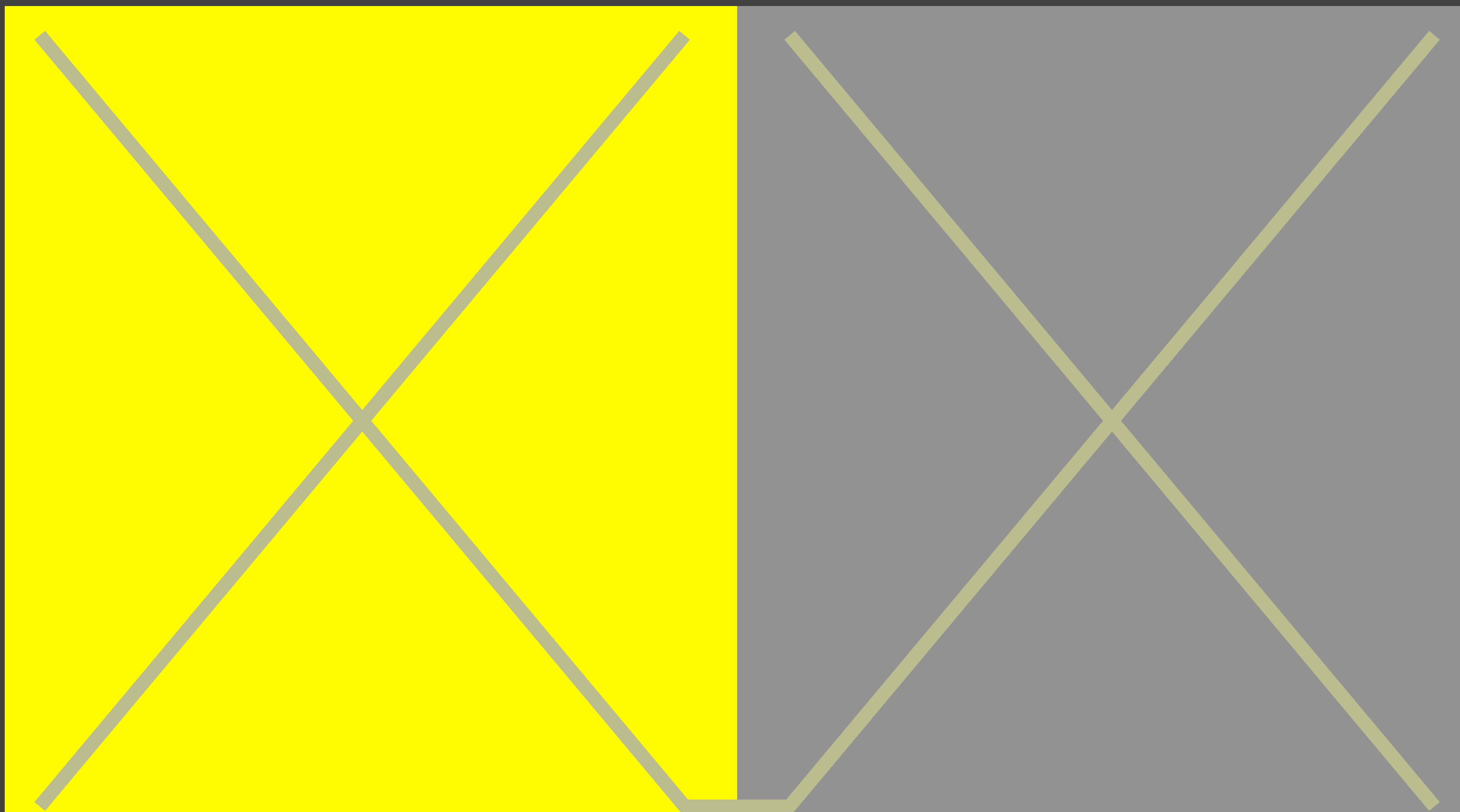
# Color Appearance

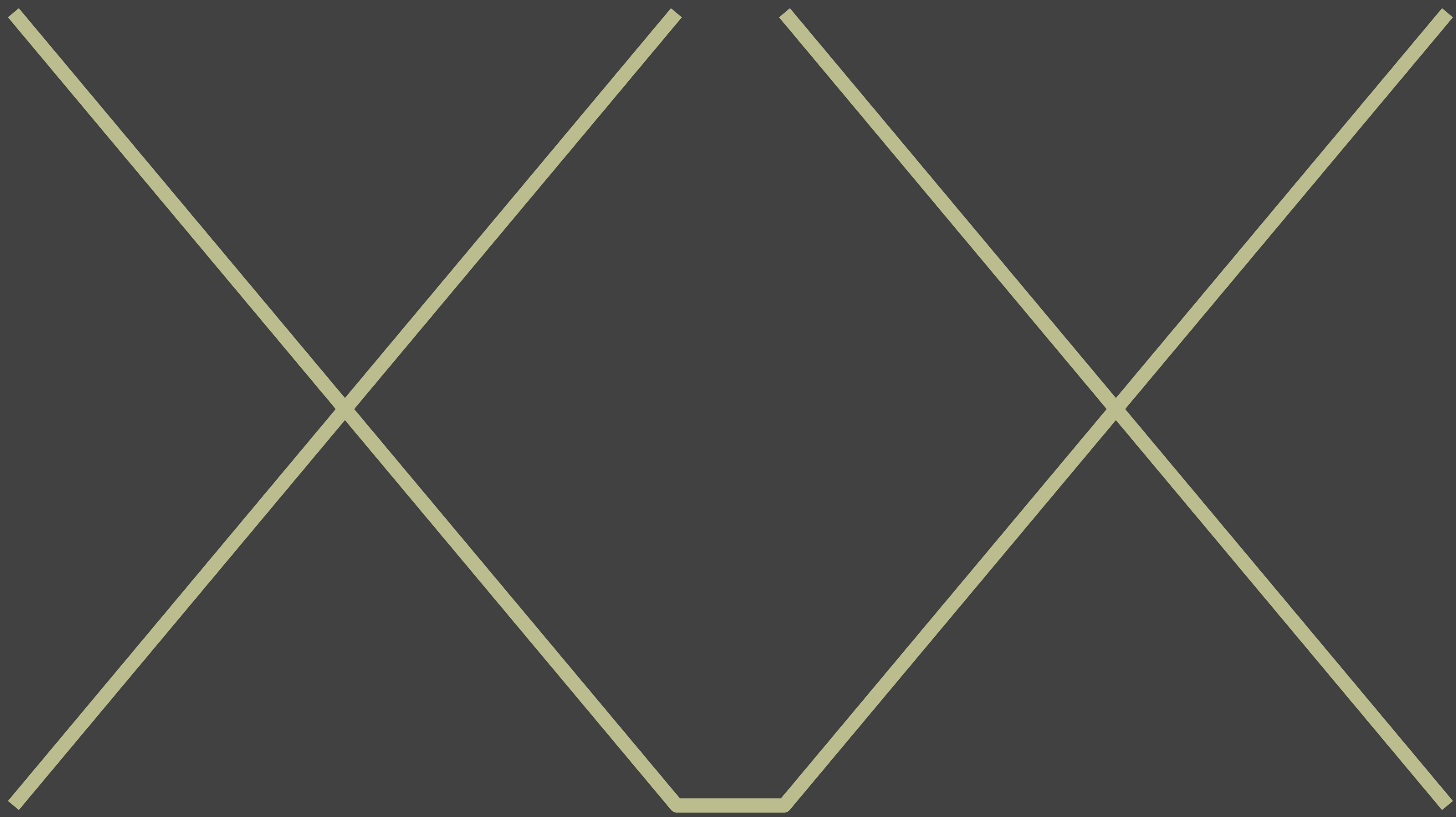
If we have a perceptually-uniform color space, can we predict how we perceive colors?

**“In order to use color effectively it is necessary to recognize that it deceives continually.”**

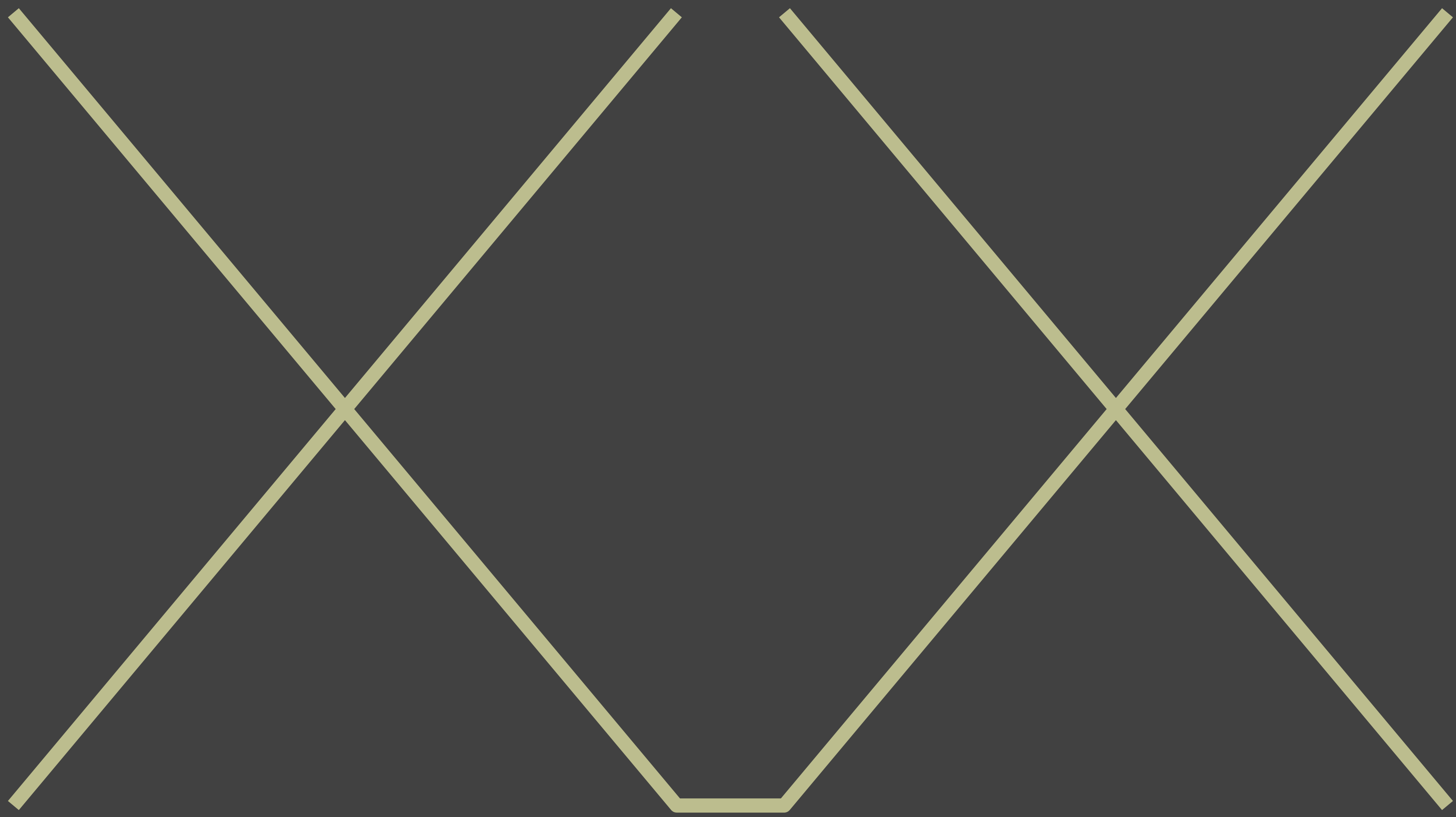
- Josef Albers, *Interaction of Color*





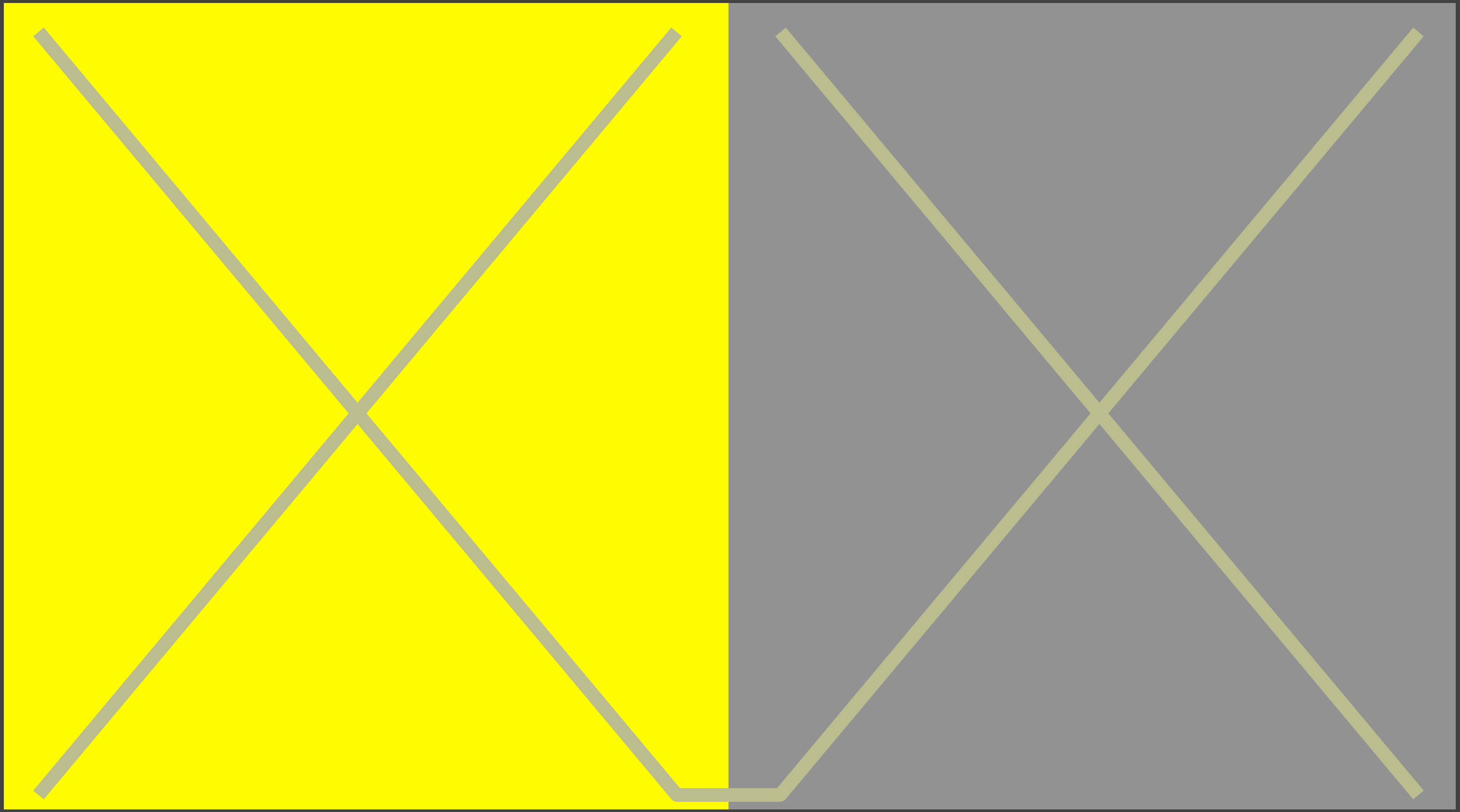


# Simultaneous Contrast



Josef Albers

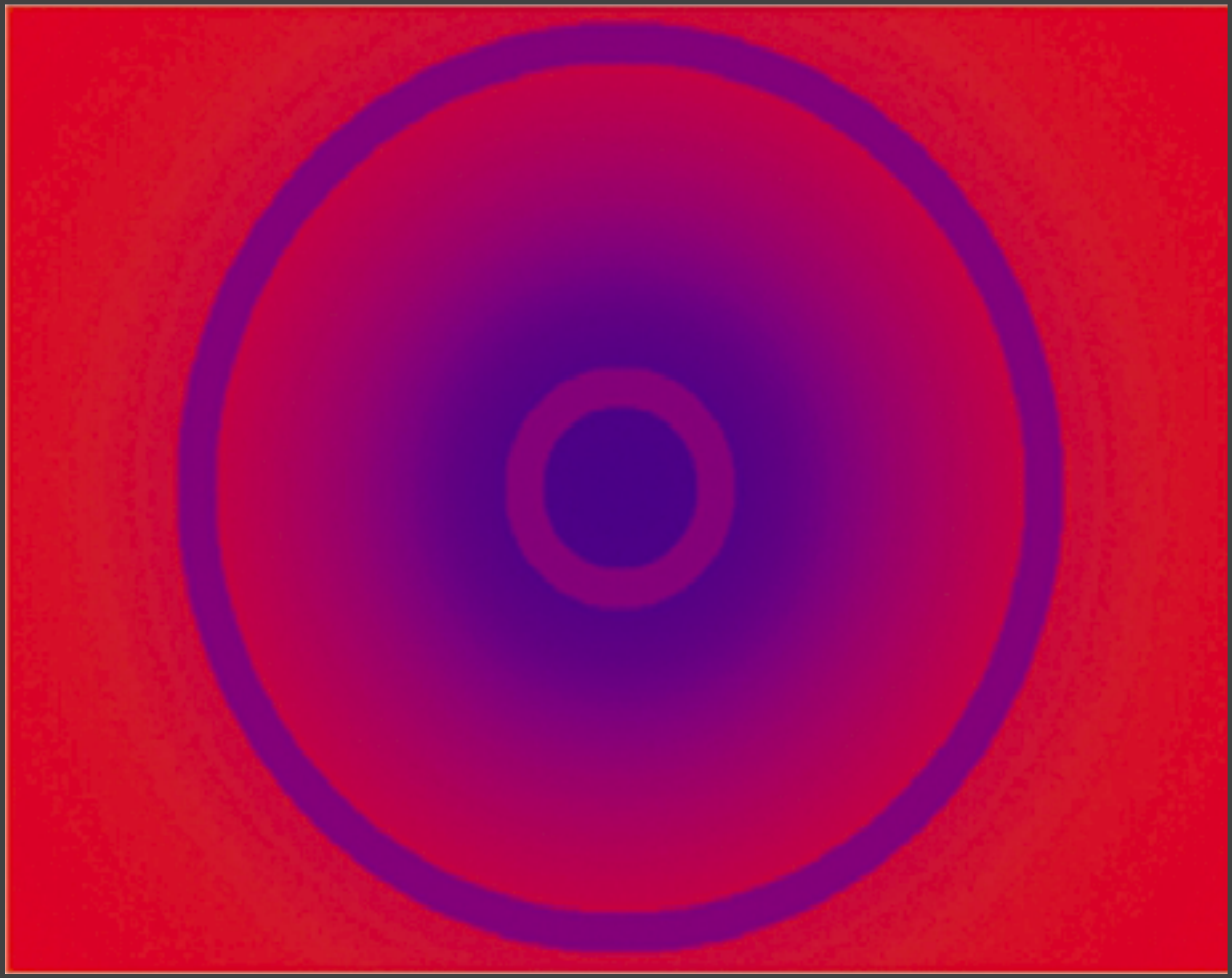
# Simultaneous Contrast



Josef Albers

# Simultaneous Contrast

Inner & outer rings are the same physical purple.



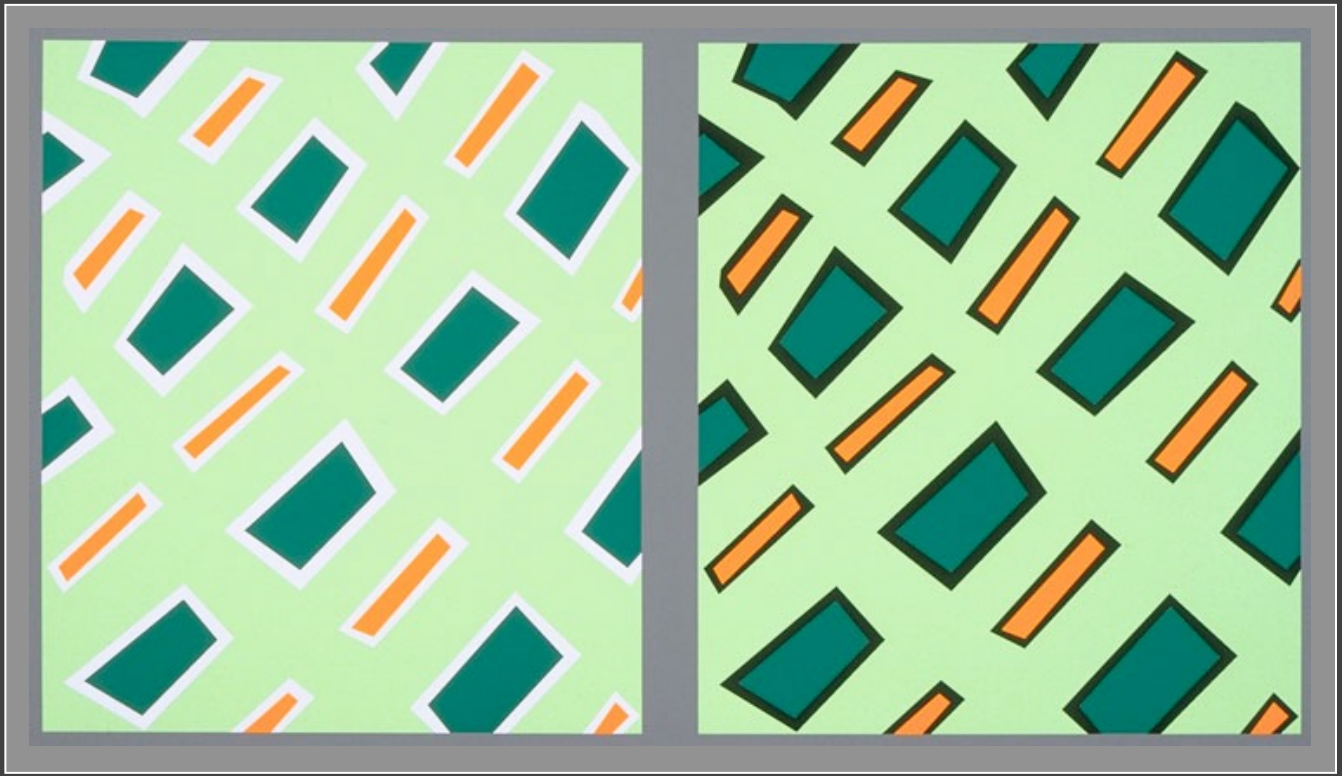
Donald MacLeod

# Chromatic Adaptation

# Chromatic Adaptation

# Bezold Effect

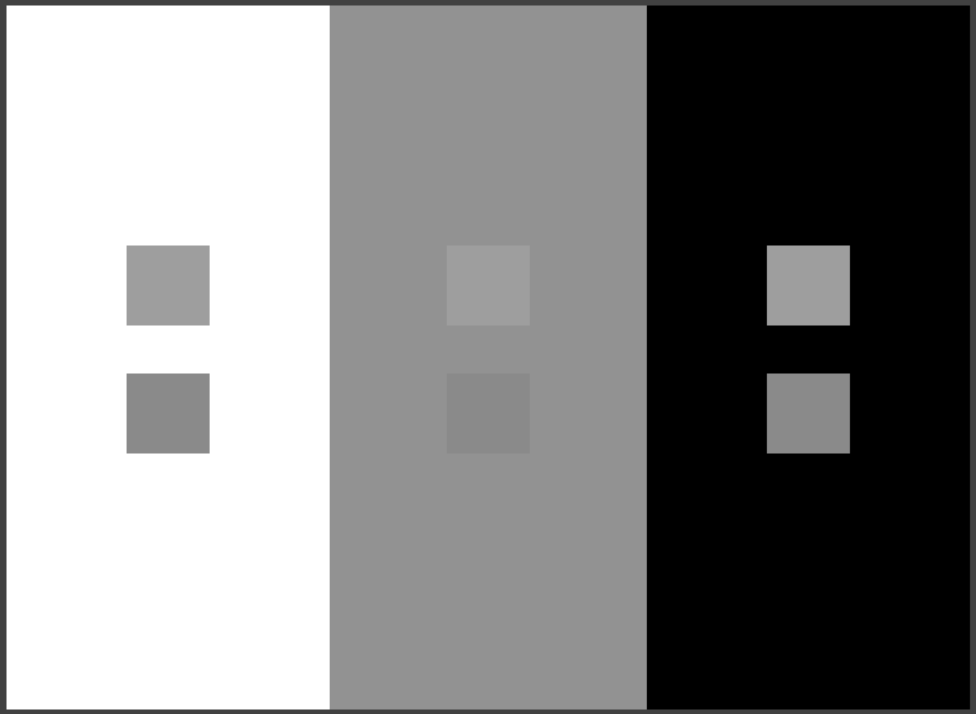
Color appearance depends on adjacent colors



Color Appearance Tutorial by Maureen Stone

# Crispening

Perceived difference depends on background



*Color Appearance Models*, Fairchild

# Spreading

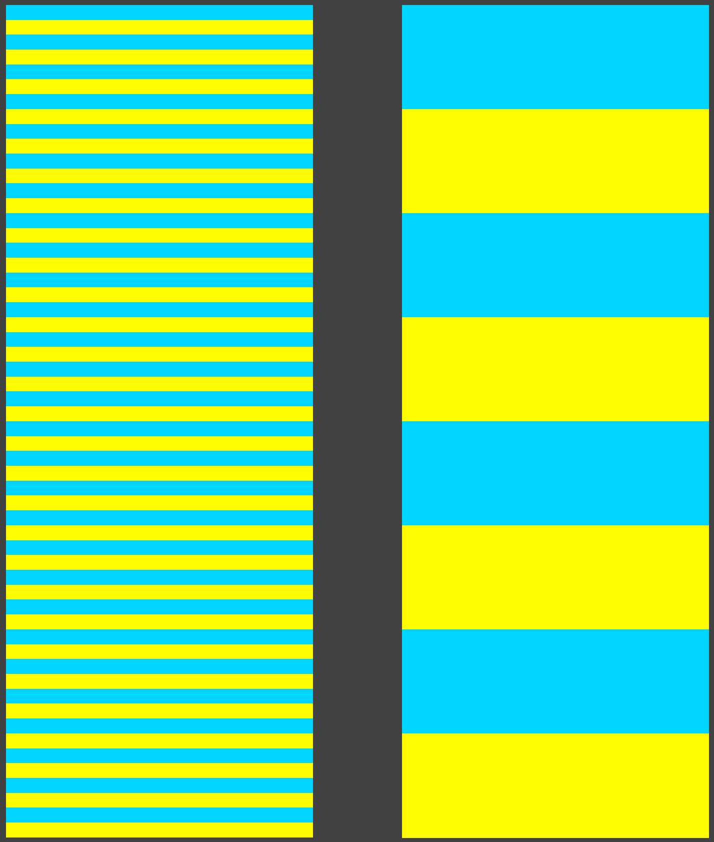
**Spatial frequency**

The paint chip problem

Small text, lines, glyphs

Image colors

**Adjacent colors blend**



*Foundations of Vision*, Brian Wandell

# Color Appearance

If we have a perceptually-uniform color space, can we predict how we perceive colors?

Chromatic adaptation

Luminance adaptation

Simultaneous contrast

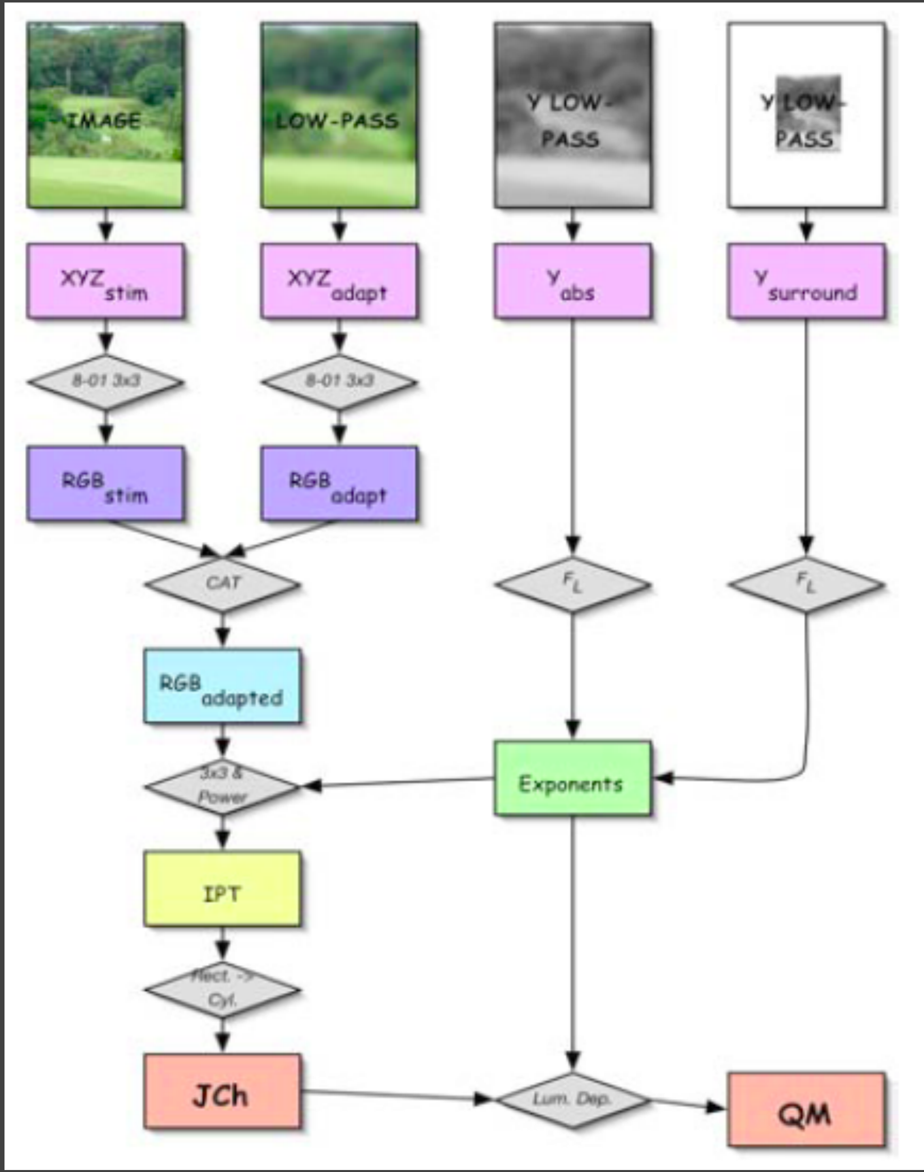
Spatial effects

Viewing angle

# iCAM

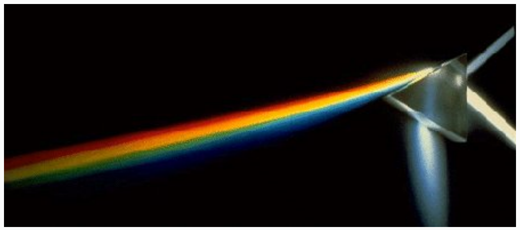
iCAM models:
Chromatic adaptation
Appearance scales
Color difference
Crispening
Spreading
HDR tone mapping

(see also **CIECAM02**)

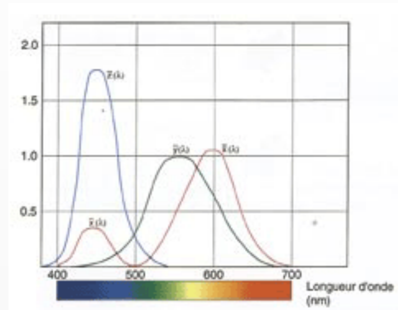



Mark Fairchild

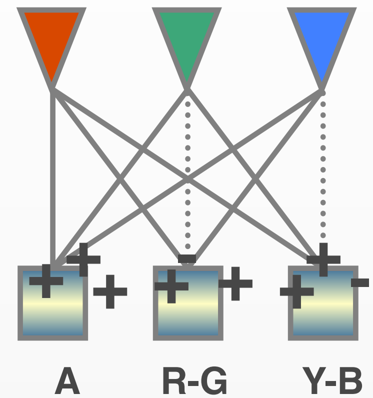
# Perception of Color



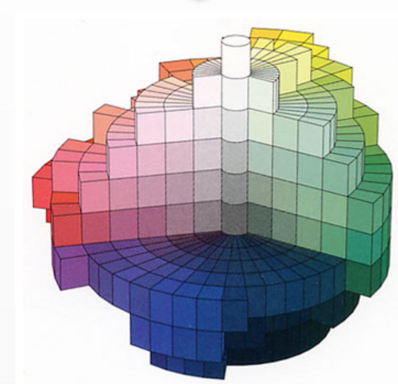
Light



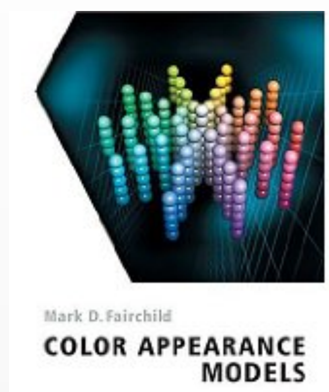

Cone Response




Opponent Signals



Color Perception




Color Appearance

"Yellow"

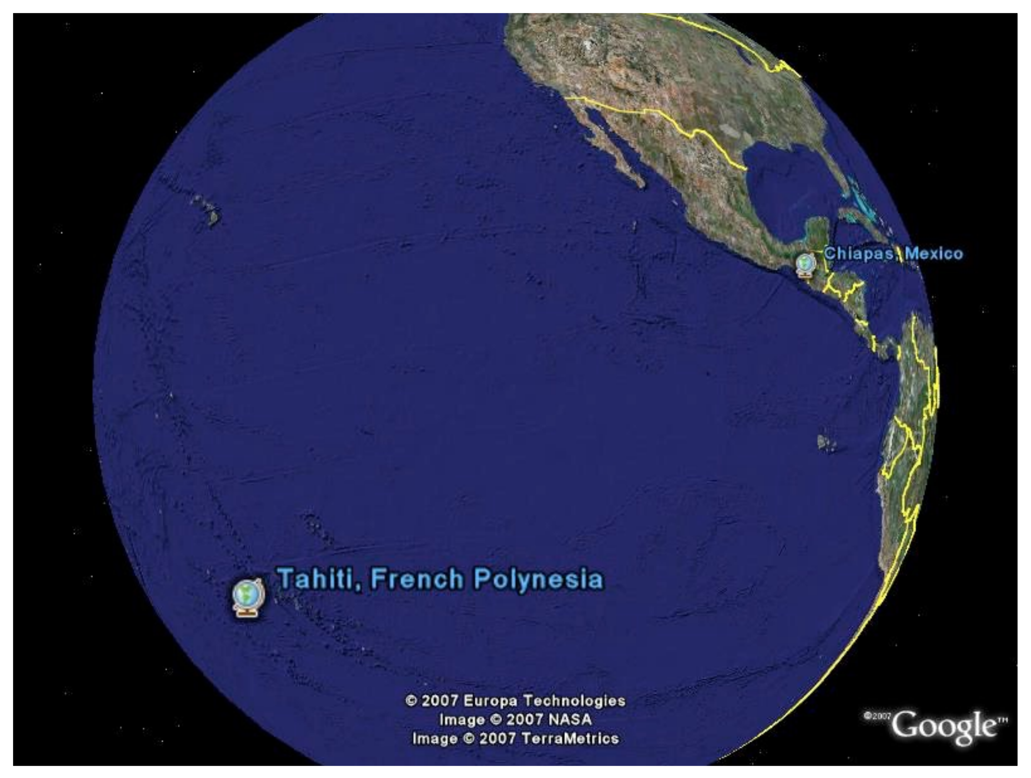
Color Cognition

# Basic Color Terms

Chance discovery by Brent Berlin and Paul Kay.

# Basic Color Terms

Chance discovery by Brent Berlin and Paul Kay.




# Basic Color Terms

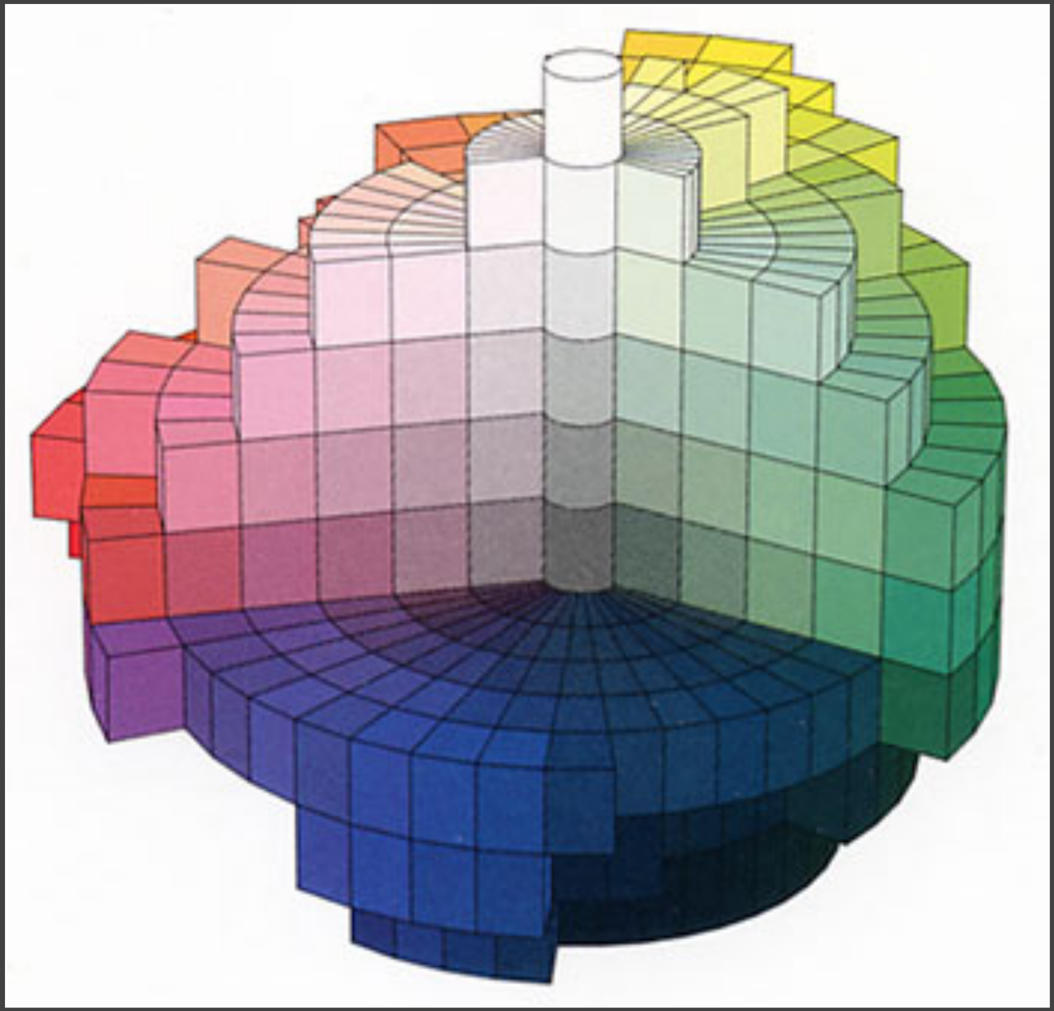
Chance discovery by Brent Berlin and Paul Kay.

Initial study in 1969

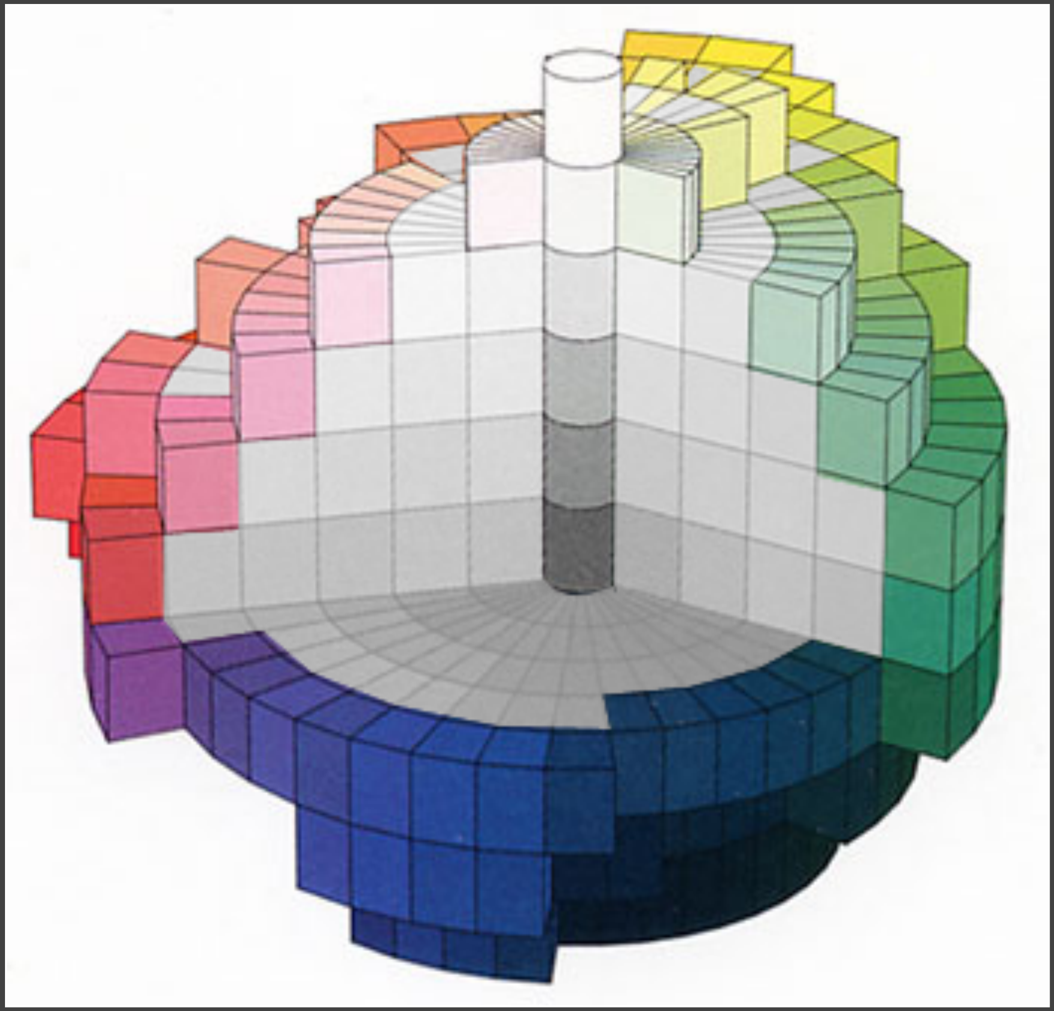
Surveyed speakers from 20 languages

Literature from 69 languages

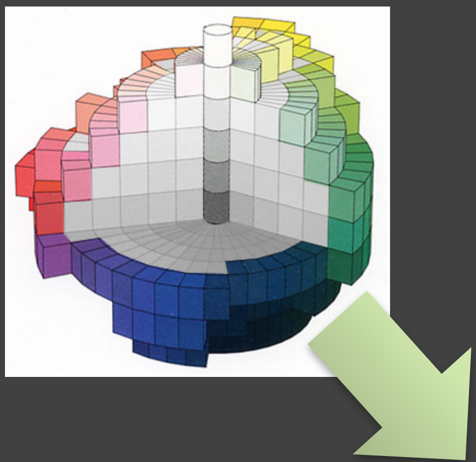
# World Color Survey



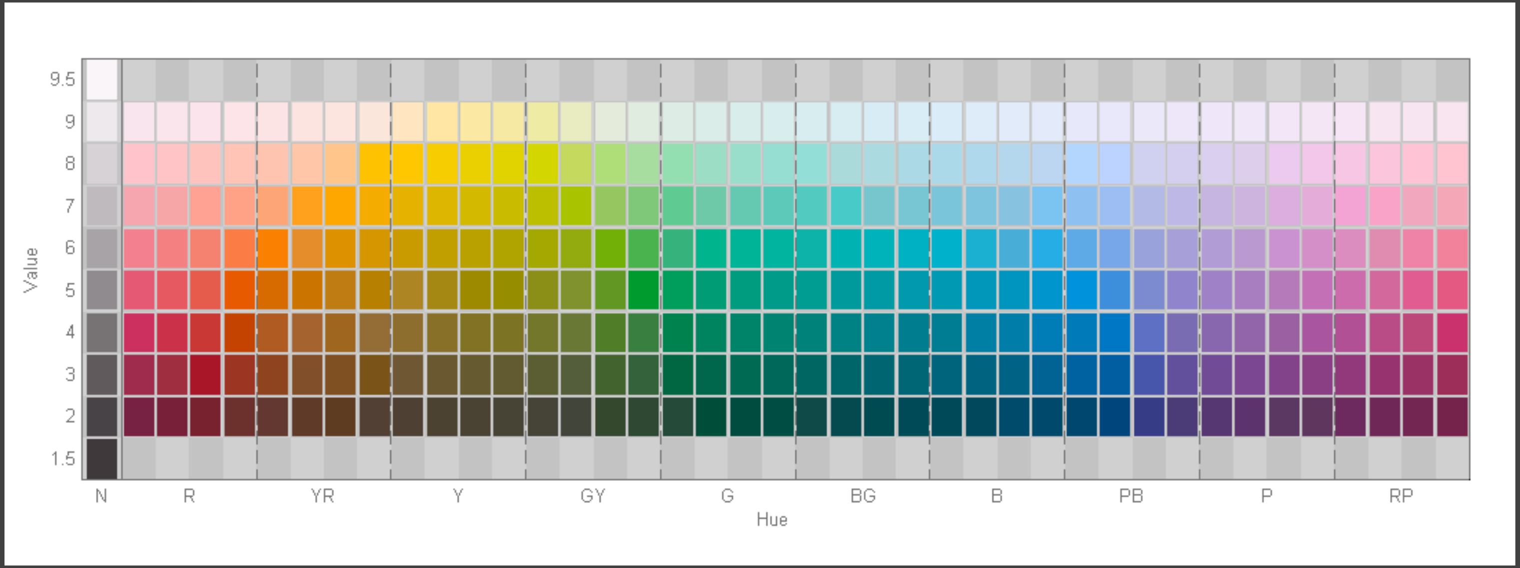
# World Color Survey



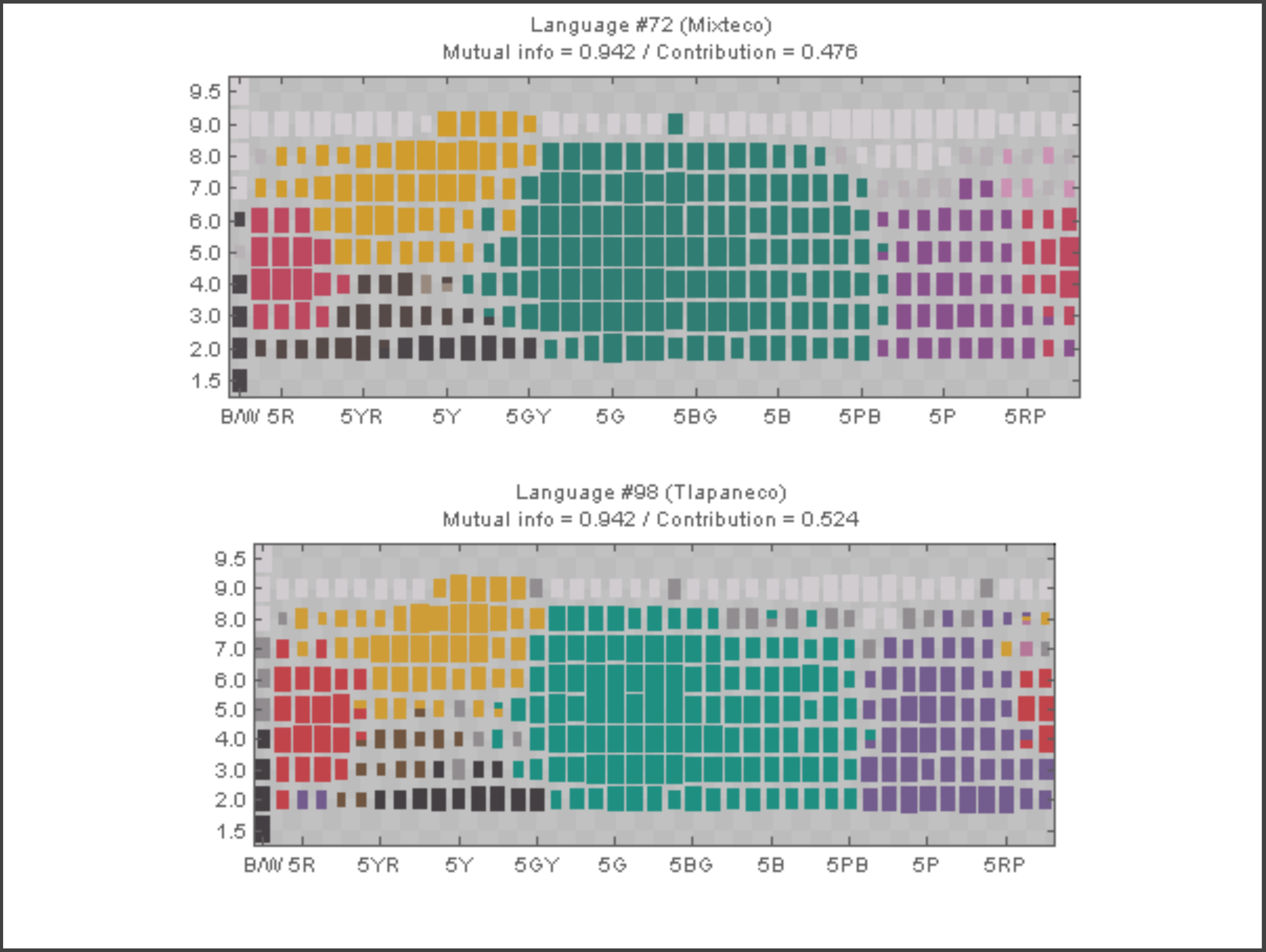
# World Color Survey



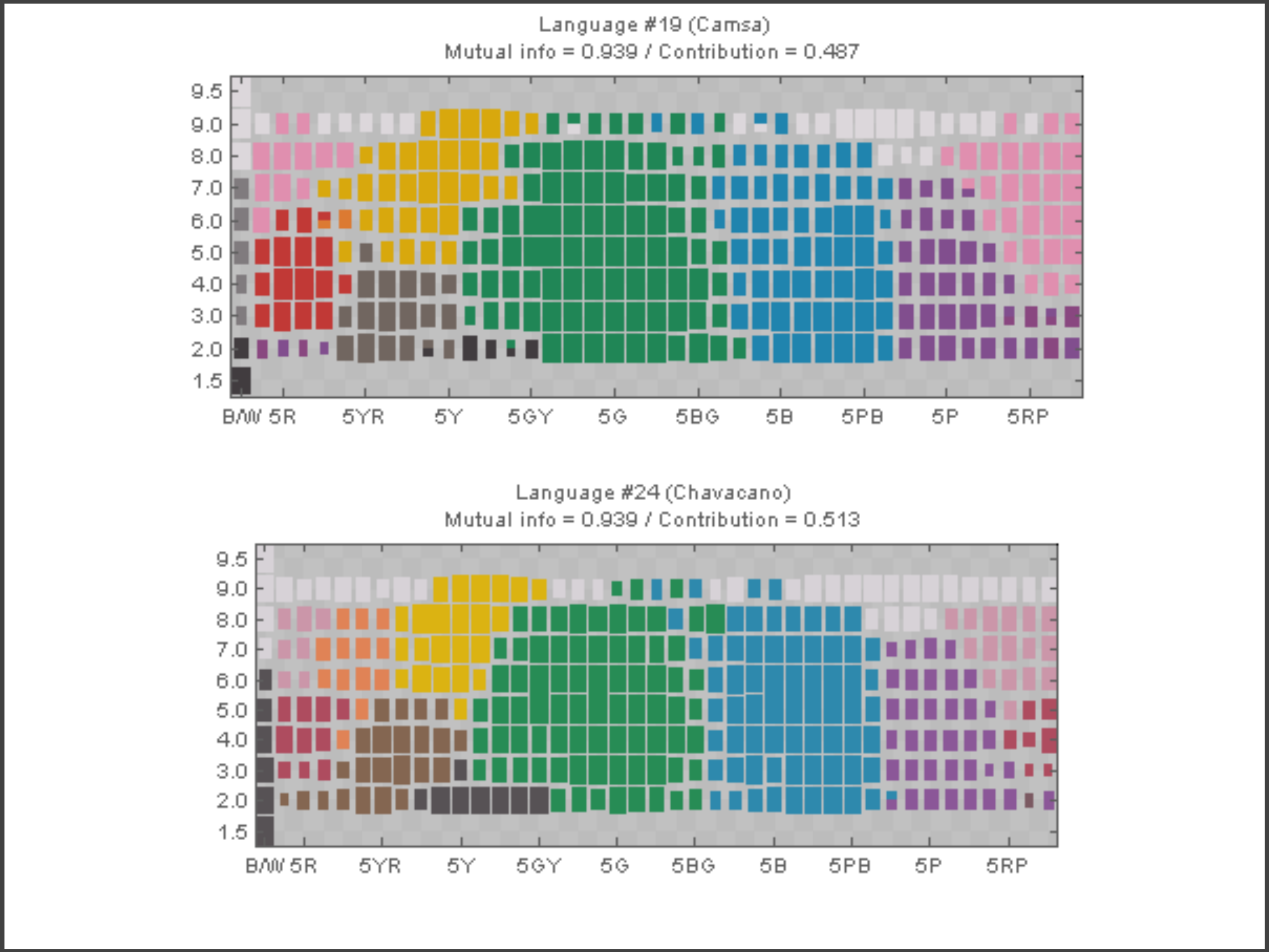
Naming information from 2616 speakers from 110 languages on 330 Munsell color chips



# Results from WCS



# Results from WCS



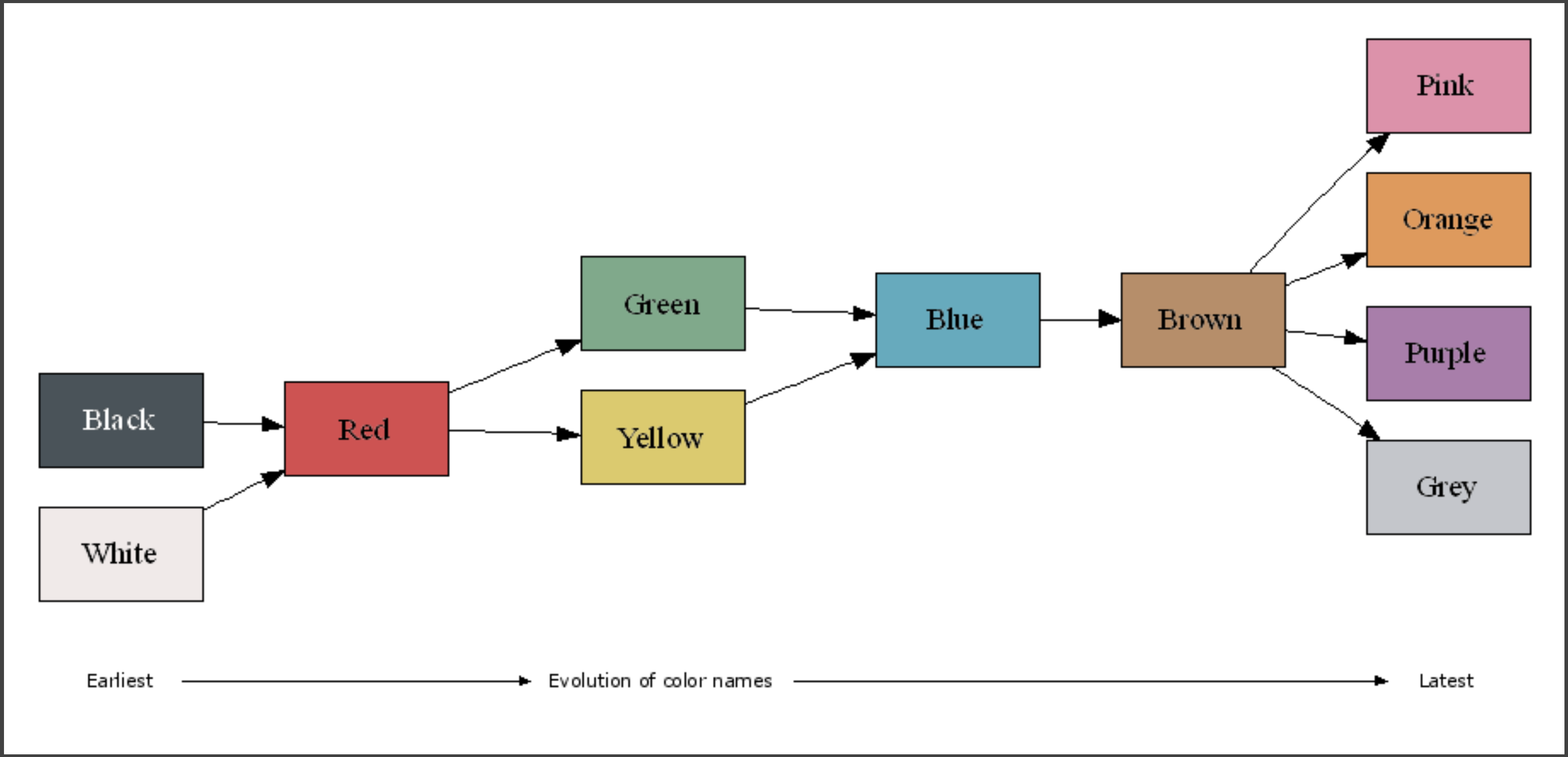
# Universal (?) Basic Color Terms

Basic color terms recur across languages.

- White
- Grey
- Black
- Red
- Yellow
- Green
- Blue
- Pink
- Brown
- Orange
- Purple

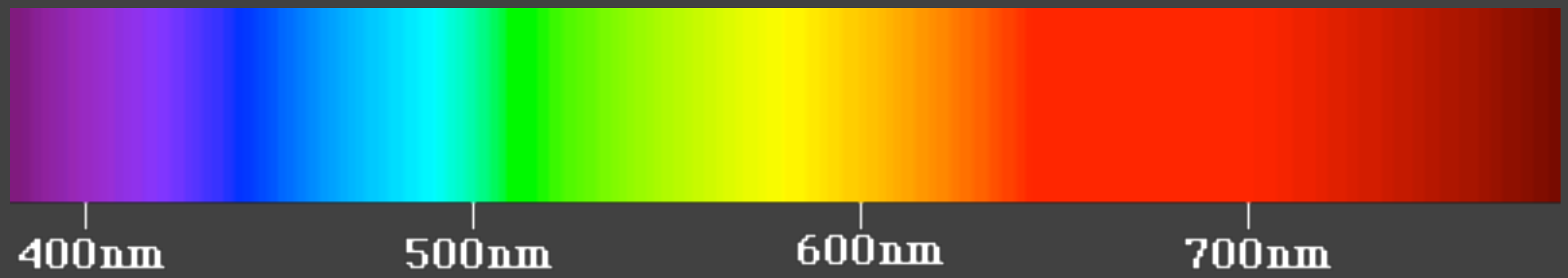
# Evolution of Basic Color Terms

Proposed universal evolution across languages.



# Rainbow Color Map

We associate and group colors together, often using the name we assign to the colors.



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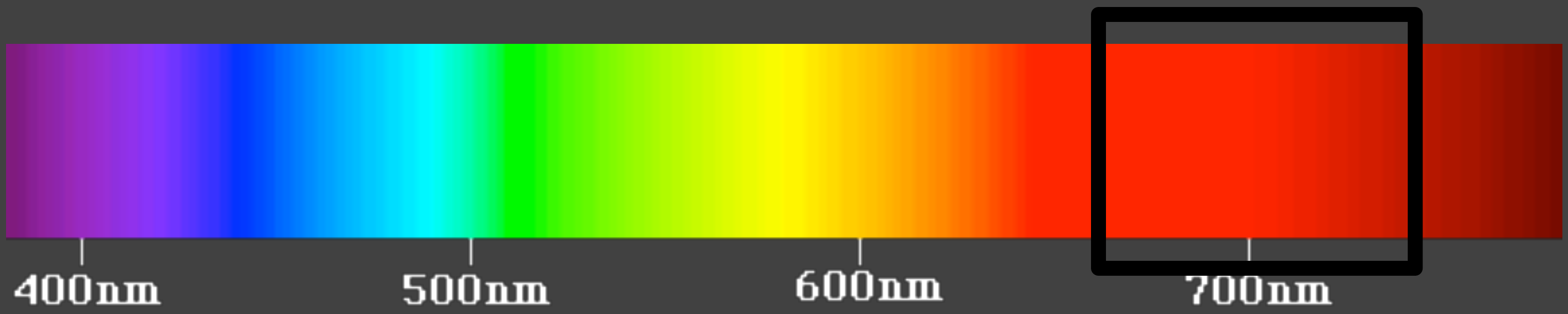

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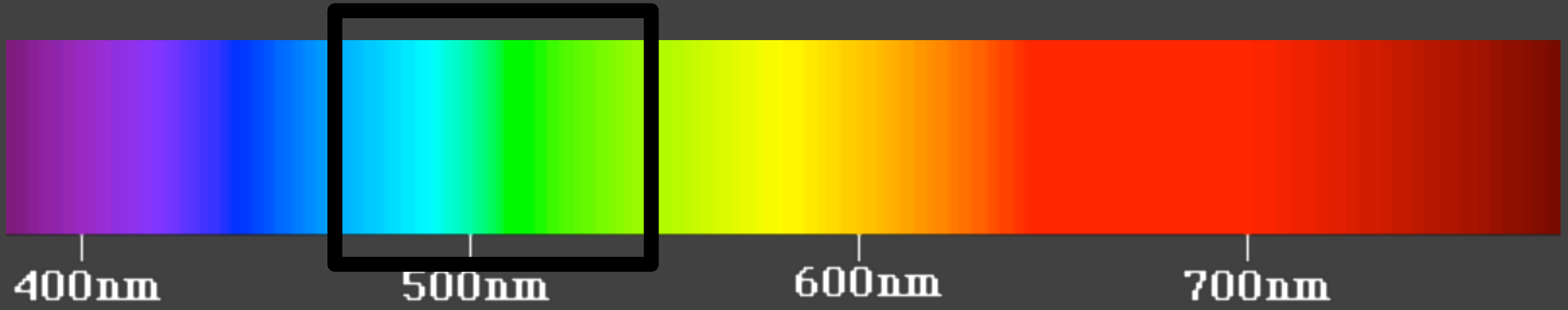
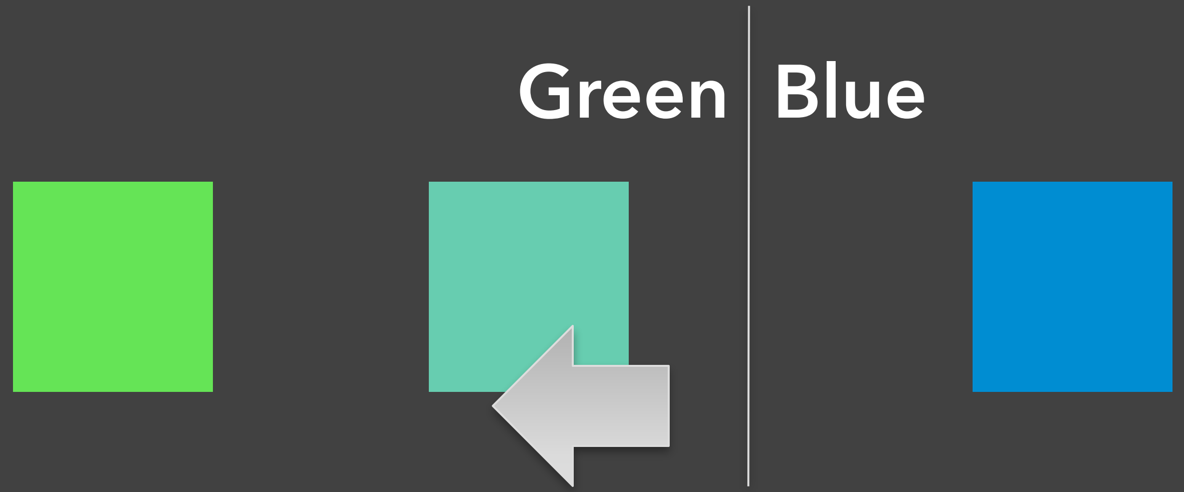
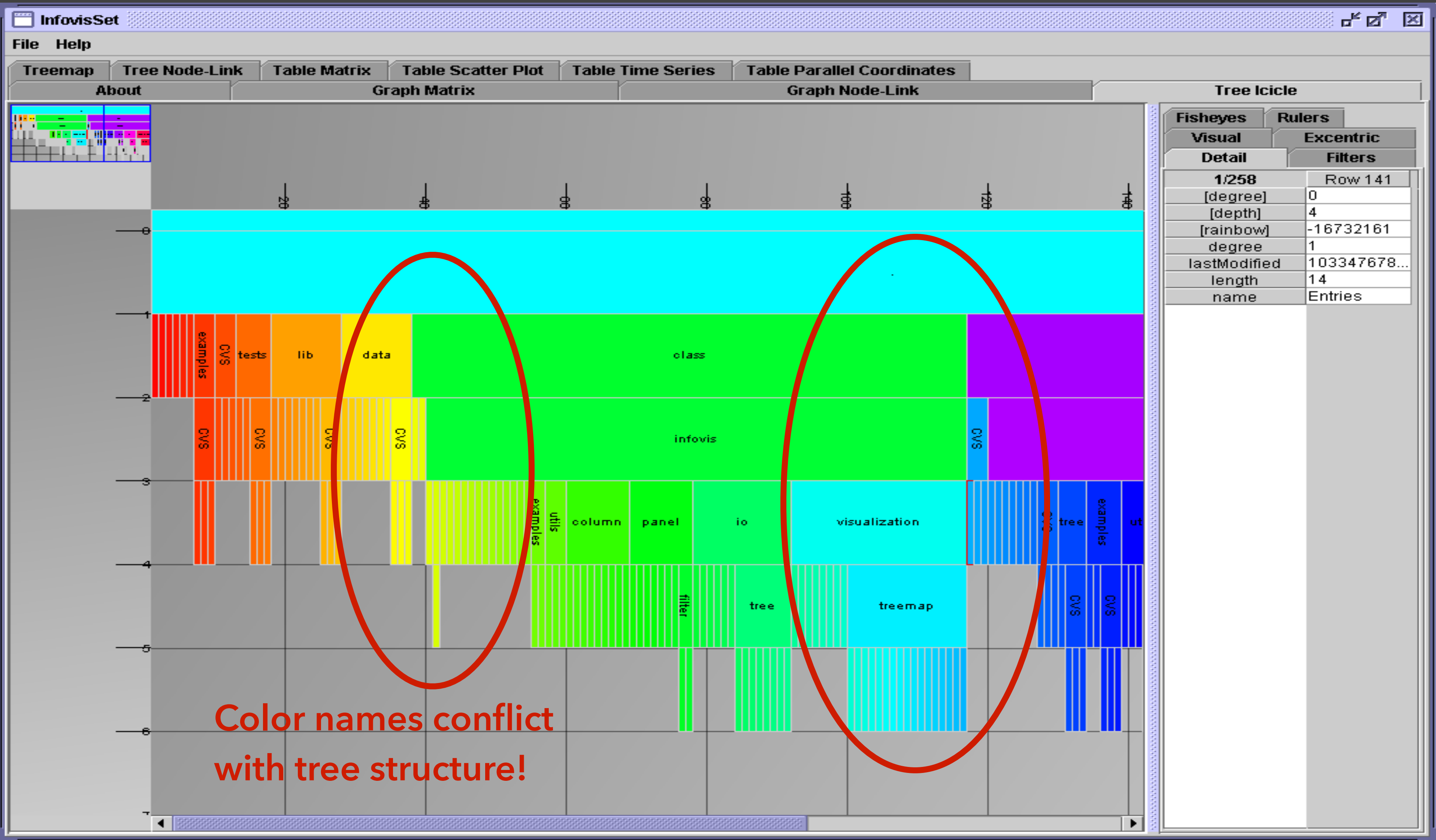


# Naming Effects Color Perception

Color name boundaries



# Icicle Tree with Rainbow Coloring




Color names conflict with tree structure!

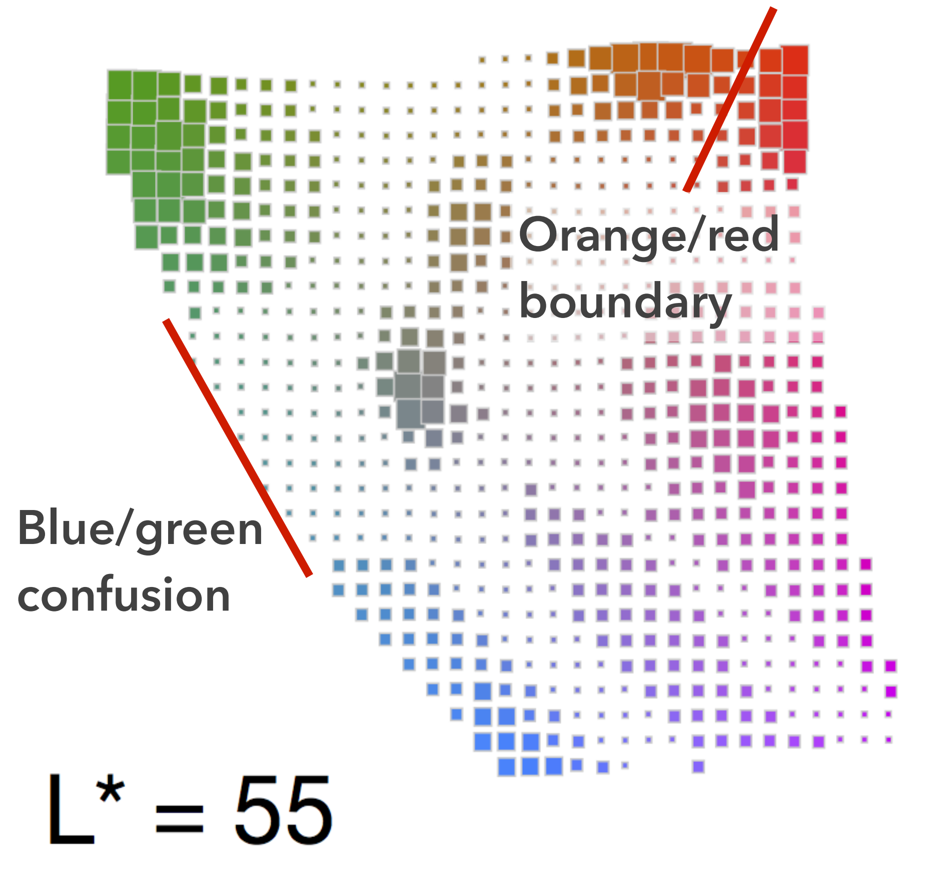
# Color Naming Models [Heer & Stone '12]

Model 3 million responses from XKCD survey

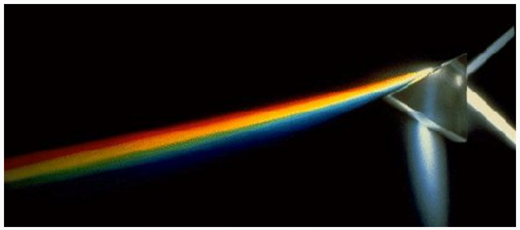
Bins in LAB space sized by *saliency*:

How much do people agree on color name?

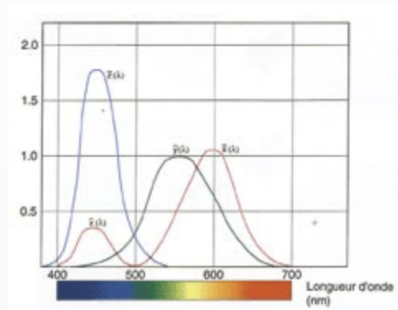
Modeled by entropy of *p(name | color)*



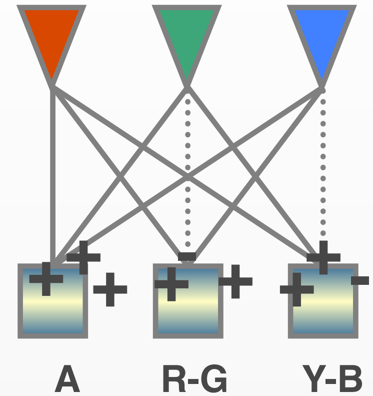
# Perception of Color



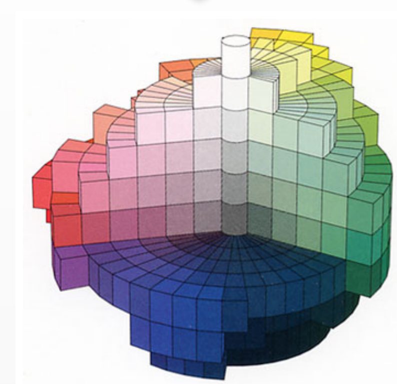
Light



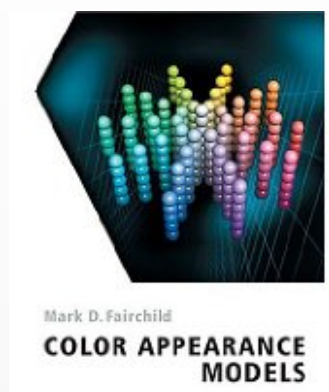

Cone Response




Opponent Signals



Color Perception




Color Appearance

**"Yellow"**

Color Cognition

# Administrivia

# A3 Peer Review

*Available on Canvas*

**I like -** Identify some things that you like about the project.
**I wish -** Identify alternative designs or interactions that you wish the authors had explored.

**What if? -** Think about any outside the box alternatives that the authors may not have considered

# Final Project is Posted!

Details on course website.

**Interactive Dashboard.** Create an interactive dashboard appropriate for an interested general audience. The dashboard might allow users to interactively explore a dataset, or serve as a display that updates over time as new data becomes available.

**Explorable Explanation.** Create an interactive article that explains a technical subject to the reader. The topic could be a computer science algorithm, a mathematical proof, a scientific phenomenon, or some other topic that you're passionate about.

# Final Project Milestones!

**Proposal.** Submit a Google Form with your team members and your idea. You can keep groups the same or switch.

**Initial Prototype.** Complete an initial prototype before the feedback sessions so we can offer constructive help.

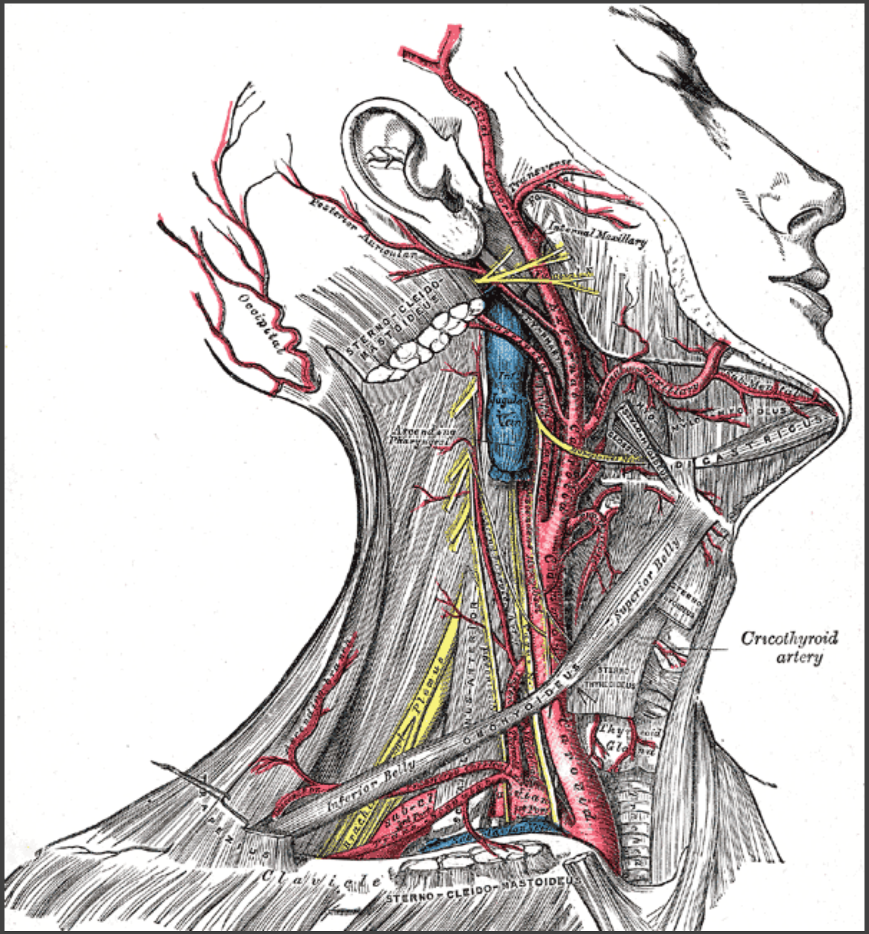
**Design feedback sessions.** Meet with course staff to check in and get feedback and advice on your designs.

**Final Deliverables and showcase.** Demo videos will be shown in class. Must also have GitHub URL.

# Designing Colormaps

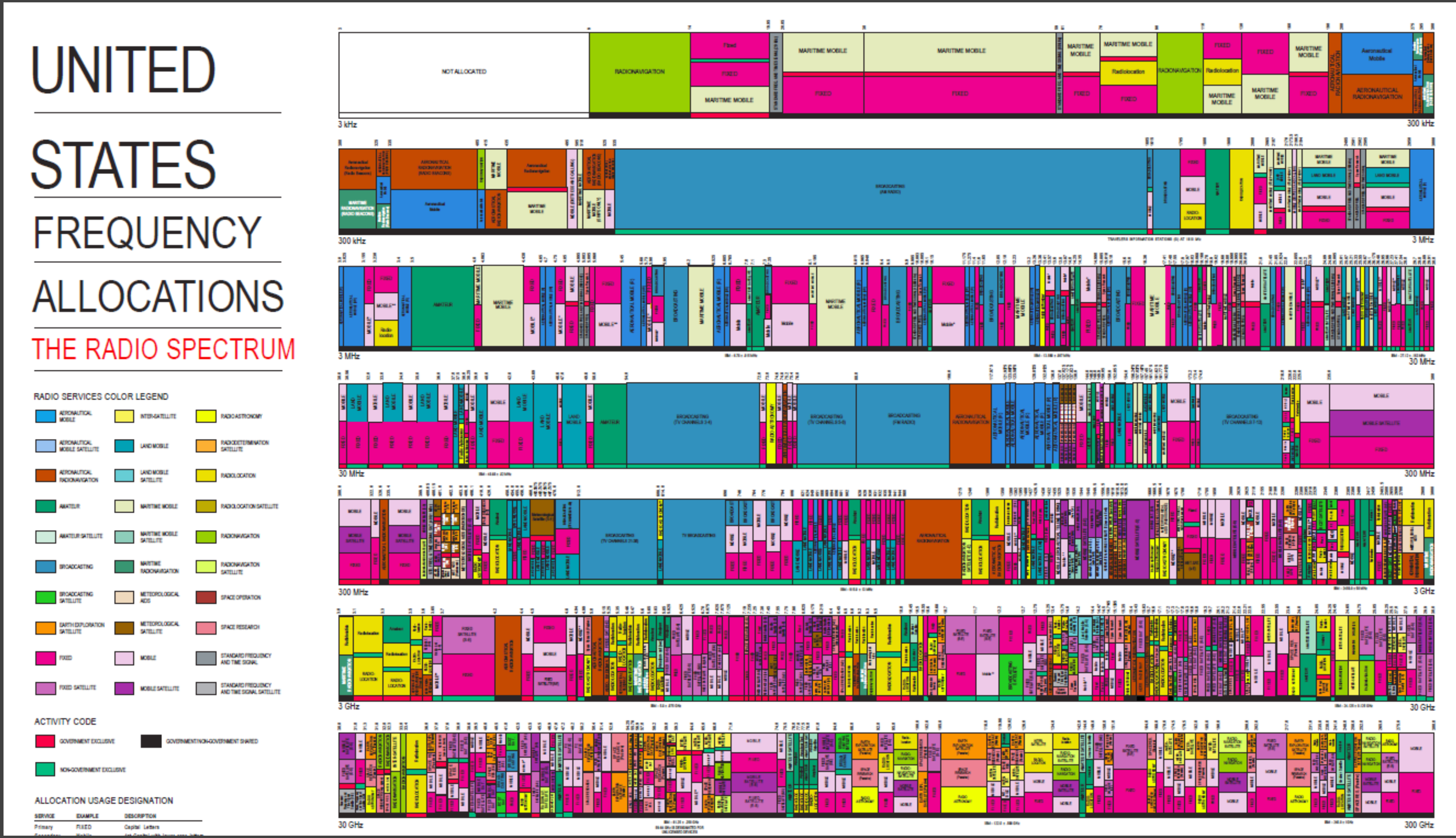
# Categorical Color

# Gray's Anatomy

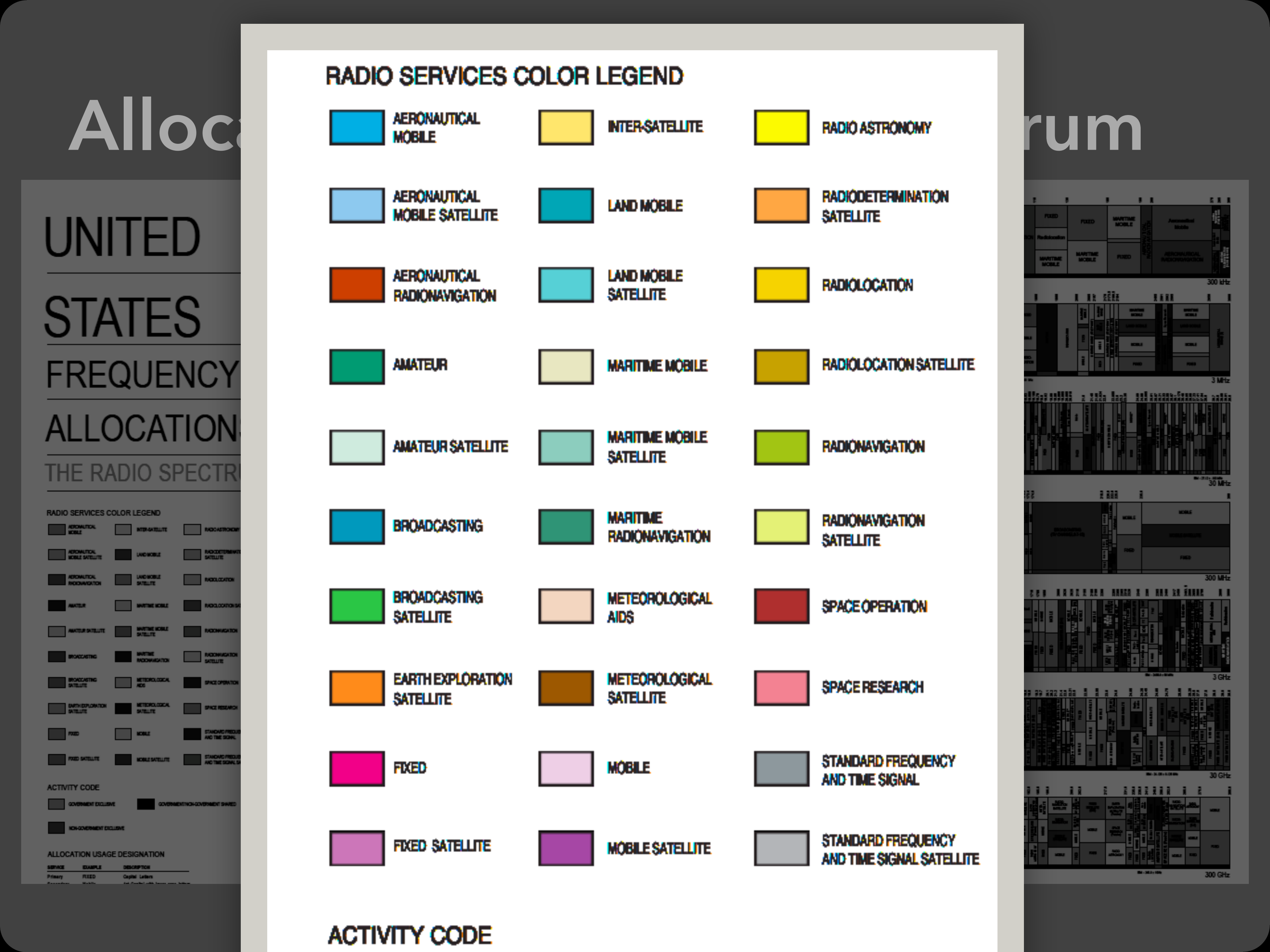



Superficial dissection of the right side of the neck, showing the carotid and subclavian arteries. (http://www.bartleby.com/107/illus520.html)

# Allocation of the Radio Spectrum




http://www.ntia.doc.gov/osmhome/allochrt.html




## RADIO SERVICES COLOR LEGEND

AERONAUTICAL MOBILE
INTER-SATELLITE
RADIO ASTRONOMY
AERONAUTICAL MOBILE SATELLITE
LAND MOBILE
RADIODETERMINATION SATELLITE
AERONAUTICAL RADIONAVIGATION
LAND MOBILE SATELLITE
RADIOLOCATION
AMATEUR
MARITIME MOBILE
RADIOLOCATION SATELLITE
AMATEUR SATELLITE
MARITIME MOBILE SATELLITE
RADIONAVIGATION
BROADCASTING
MARITIME RADIONAVIGATION
RADIONAVIGATION SATELLITE
BROADCASTING SATELLITE
METEOROLOGICAL AIDS
SPACE OPERATION
EARTH EXPLORATION SATELLITE
METEOROLOGICAL SATELLITE
SPACE RESEARCH
FIXED
MOBILE
STANDARD FREQUENCY AND TIME SIGNAL
FIXED SATELLITE
MOBILE SATELLITE
STANDARD FREQUENCY AND TIME SIGNAL SATELLITE

## ACTIVITY CODE

# Palette Design & Color Names

Minimize overlap and ambiguity of colors.

| Color Name Distance | | | | | | | | | | Salience | Name |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 0.00 | 1.00 | 1.00 | 1.00 | 0.98 | 1.00 | 1.00 | 1.00 | 1.00 | 0.20 | .47 | **blue** 62.9% |
| 1.00 | 0.00 | 1.00 | 0.97 | 1.00 | 1.00 | 1.00 | 1.00 | 0.96 | 1.00 | .90 | **orange** 93.9% |
| 1.00 | 1.00 | 0.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 0.90 | 0.99 | .67 | **green** 79.8% |
| 1.00 | 0.97 | 1.00 | 0.00 | 1.00 | 0.95 | 0.99 | 1.00 | 1.00 | 1.00 | .66 | **red** 80.4% |
| 0.98 | 1.00 | 1.00 | 1.00 | 0.00 | 0.96 | 0.91 | 0.97 | 1.00 | 0.99 | .47 | **purple** 51.4% |
| 1.00 | 1.00 | 1.00 | 0.95 | 0.96 | 0.00 | 0.97 | 0.93 | 0.98 | 1.00 | .37 | **brown** 54.0% |
| 1.00 | 1.00 | 1.00 | 0.99 | 0.91 | 0.97 | 0.00 | 1.00 | 1.00 | 1.00 | .58 | **pink** 71.7% |
| 1.00 | 1.00 | 1.00 | 1.00 | 0.97 | 0.93 | 1.00 | 0.00 | 1.00 | 1.00 | .67 | **grey** 79.4% |
| 1.00 | 0.96 | 0.90 | 1.00 | 1.00 | 0.98 | 1.00 | 1.00 | 0.00 | 1.00 | .18 | **yellow** 31.2% |
| 0.20 | 1.00 | 0.99 | 1.00 | 0.99 | 1.00 | 1.00 | 1.00 | 1.00 | 0.00 | .25 | **blue** 25.4% |
| **Tableau-10** | | | | | | | | *Average* | *0.97* | .52 | |

http://vis.stanford.edu/color-names

# Palette Design & Color Names

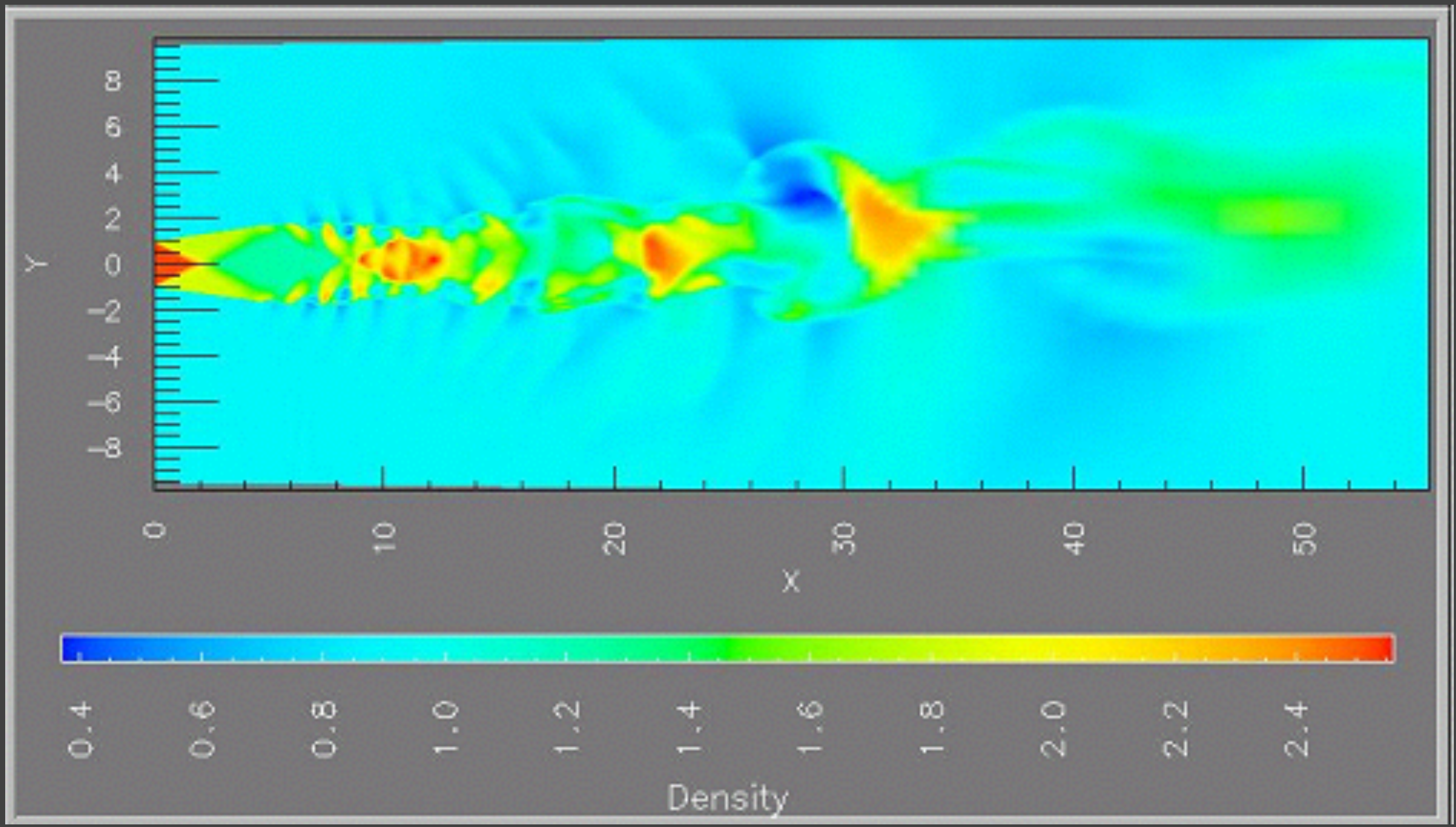
Minimize overlap and ambiguity of colors.

| Color Name Distance | | | | | | | | | | Salience | Name |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 0.00 | 1.00 | 1.00 | 0.89 | 0.07 | 1.00 | 0.35 | 0.99 | 1.00 | 0.89 | .30 | **blue** 50.5% |
| 1.00 | 0.00 | 0.99 | 1.00 | 1.00 | 0.92 | 1.00 | 0.84 | 0.98 | 0.99 | .21 | **red** 27.8% |
| 1.00 | 0.99 | 0.00 | 1.00 | 0.98 | 1.00 | 1.00 | 1.00 | 0.17 | 1.00 | .34 | **green** 36.8% |
| 0.89 | 1.00 | 1.00 | 0.00 | 0.98 | 1.00 | 0.71 | 0.93 | 1.00 | 0.32 | .55 | **purple** 67.3% |
| 0.07 | 1.00 | 0.98 | 0.98 | 0.00 | 1.00 | 0.36 | 1.00 | 0.97 | 0.95 | .20 | **blue** 36.6% |
| 1.00 | 0.92 | 1.00 | 1.00 | 1.00 | 0.00 | 1.00 | 0.97 | 0.99 | 1.00 | .39 | **orange** 51.9% |
| 0.35 | 1.00 | 1.00 | 0.71 | 0.36 | 1.00 | 0.00 | 0.95 | 0.92 | 0.42 | .13 | **blue** 15.7% |
| 0.99 | 0.84 | 1.00 | 0.93 | 1.00 | 0.97 | 0.95 | 0.00 | 0.98 | 0.85 | .16 | **pink** 29.4% |
| 1.00 | 0.98 | 0.17 | 1.00 | 0.97 | 0.99 | 0.92 | 0.98 | 0.00 | 0.97 | .12 | **green** 21.7% |
| 0.89 | 0.99 | 1.00 | 0.32 | 0.95 | 1.00 | 0.42 | 0.85 | 0.97 | 0.00 | .30 | **purple** 23.9% |
| **Excel-10** | | | | | | | | *Average* | *0.87* | *.27* | |

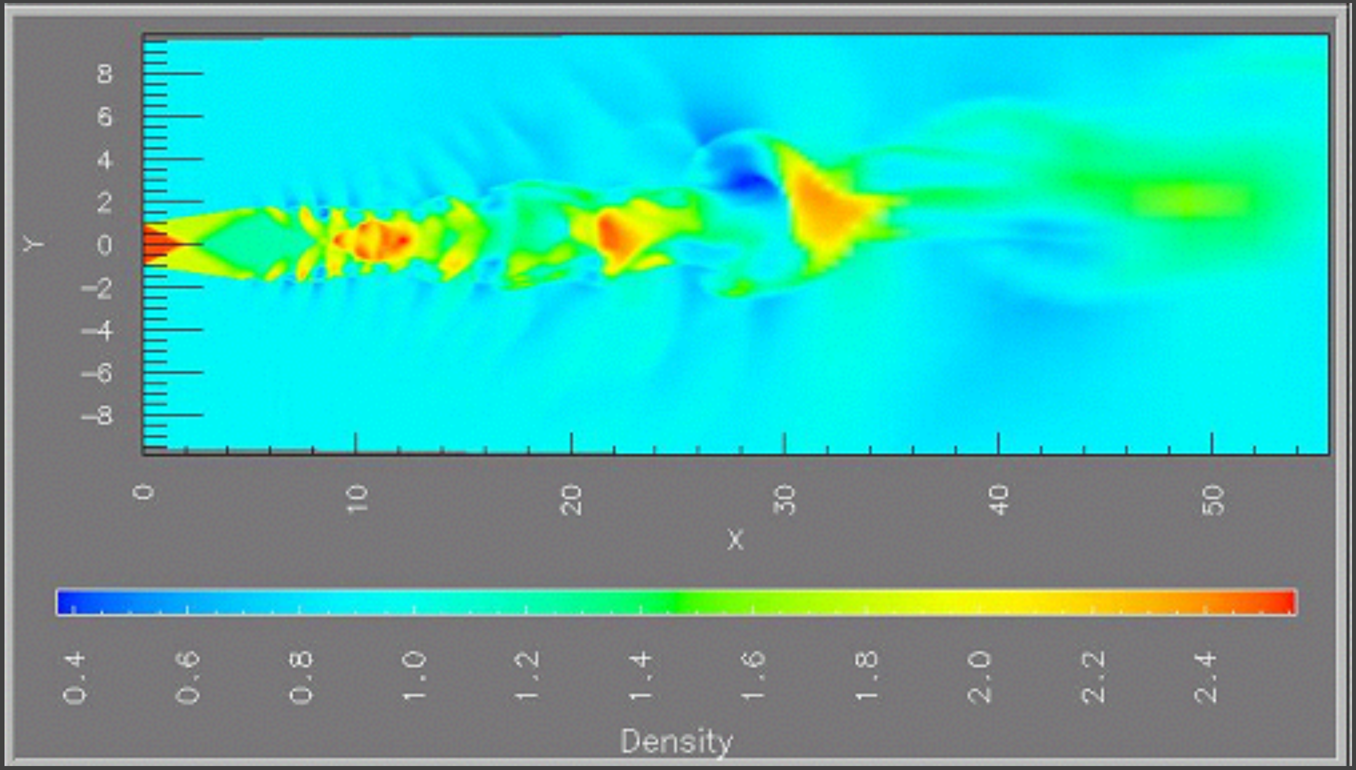
http://vis.stanford.edu/color-names

# Quantitative Color

# Rainbow Color Maps

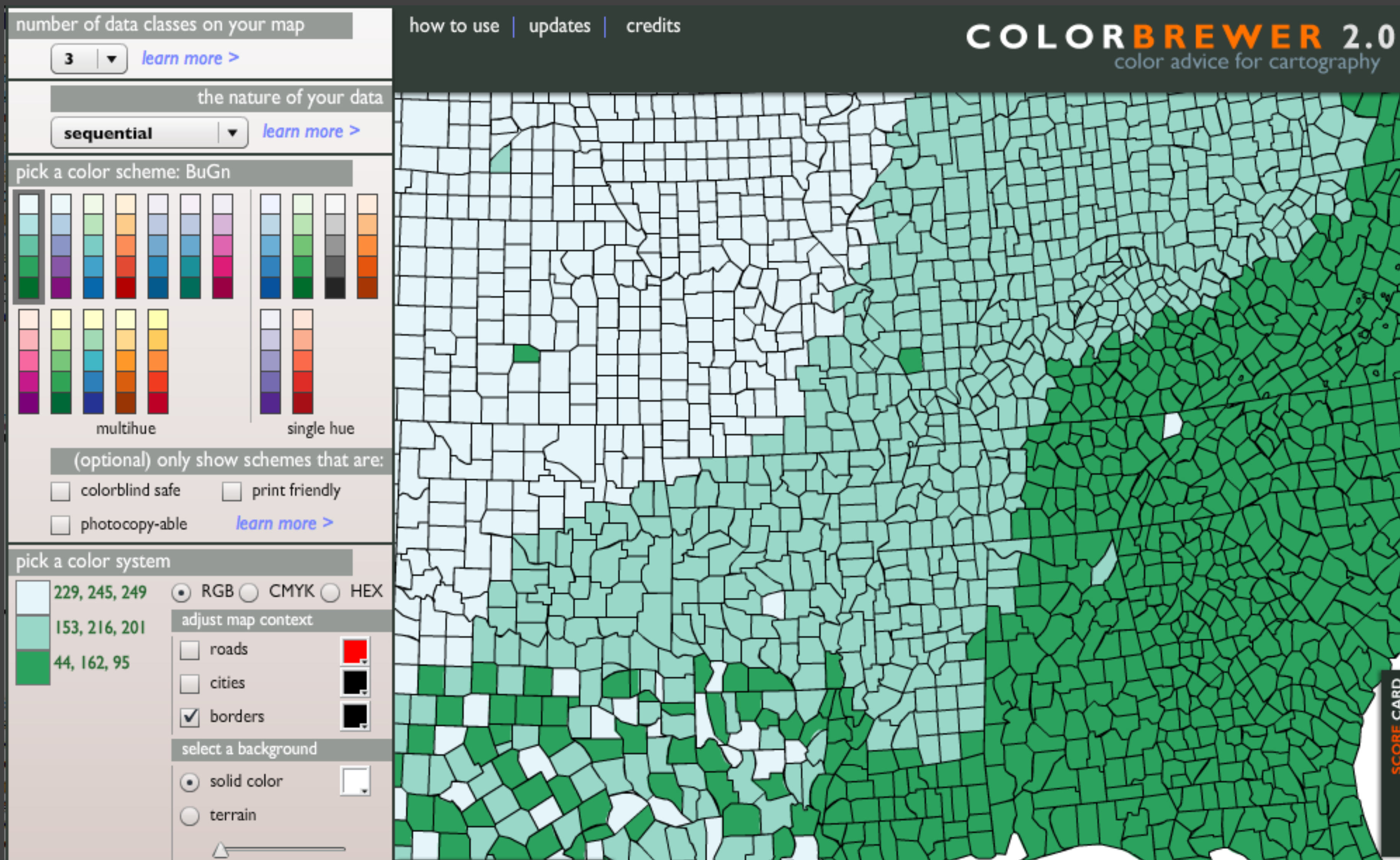


# Be Wary of Rainbows!



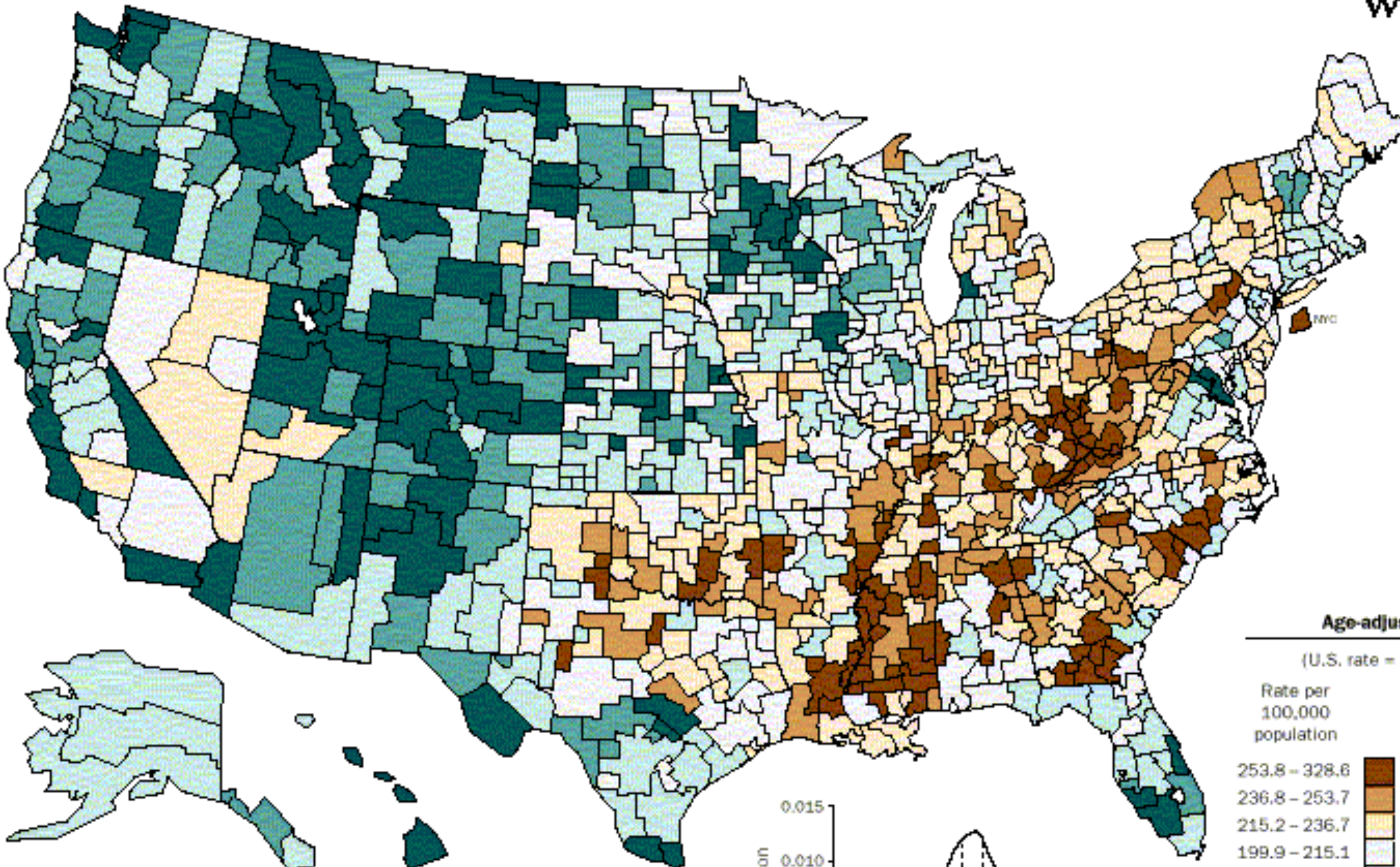

1. Hues are not naturally ordered
2. People segment colors into classes, perceptual banding
3. Naive rainbows are unfriendly to color blind viewers
4. Some colors are less effective at high spatial frequencies

# Color Brewer: Palettes for Maps



# Age-adjusted death rates by HSA, 1988-92

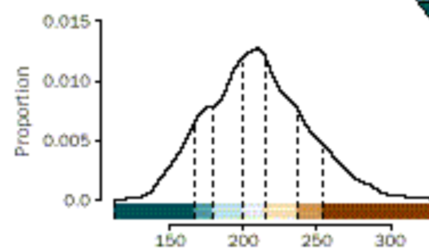
## Heart disease
## White male




**Age-adjusted**

(U.S. rate = 205.0)

| Rate per 100,000 population | Comparative mortality ratio (HSA to U.S.) |
|---|---|
| 253.8 – 328.6 | 1.24 – 1.60 |
| 236.8 – 253.7 | 1.16 – 1.24 |
| 215.2 – 236.7 | 1.05 – 1.16 |
| 199.9 – 215.1 | 0.98 – 1.05 |
| 179.5 – 199.8 | 0.88 – 0.98 |
| 166.7 – 179.4 | 0.81 – 0.88 |
| 112.4 – 166.6 | 0.55 – 0.81 |

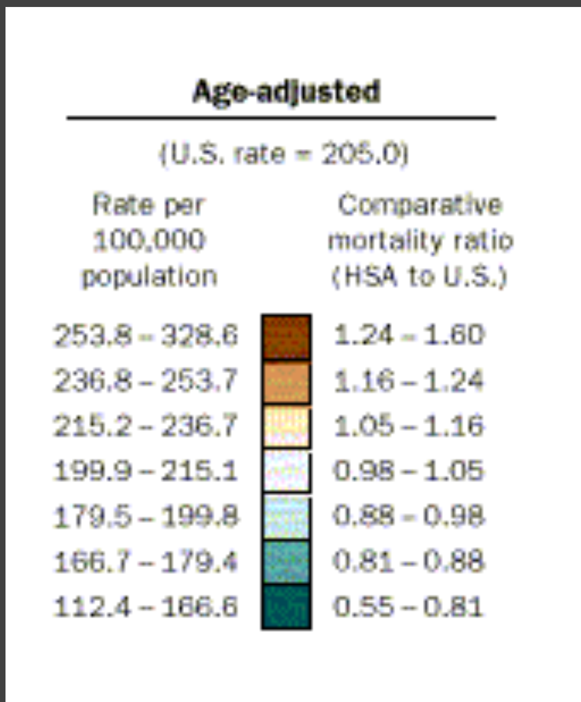


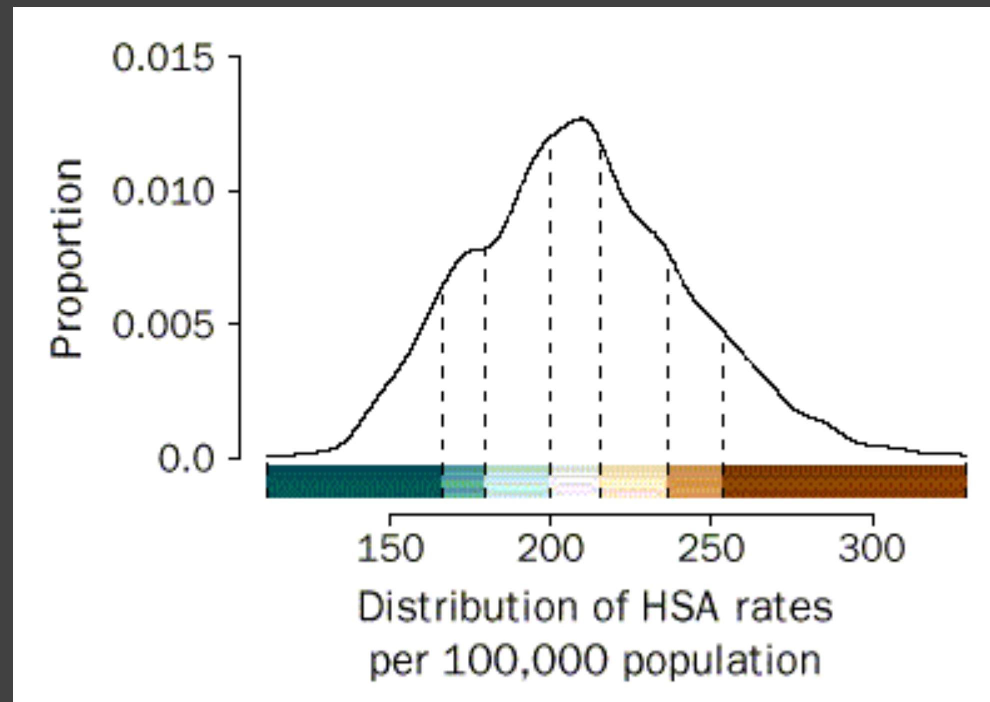

Distribution of HSA rates per 100,000 population

ICD–9 Categories 390–398, 402, 404–429

SOURCE: CDC/NCHS

# Classing Quantitative Data




Age-adjusted mortality rates for the United States.
Common option: break into 5 or 7 quantiles.

# Classing Quantitative Data

1. Equal interval (arithmetic progression)
2. Quantiles *(**recommended**)*
3. Standard deviations
4. Clustering (Jenks' natural breaks / 1D K-Means)

   Minimize within group variance

   Maximize between group variance

# Quantitative Color Encoding

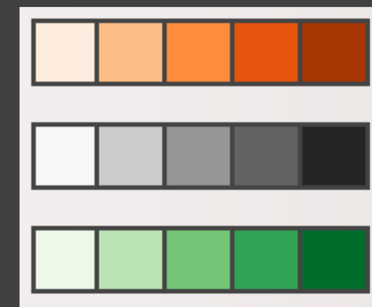
## Sequential color scale

Ramp in luminance, possibly also hue

Typically higher values map to darker colors

# Quantitative Color Encoding

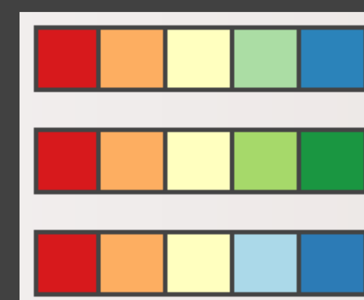
## Sequential color scale



Ramp in luminance, possibly also hue

Typically higher values map to darker colors

## Diverging color scale



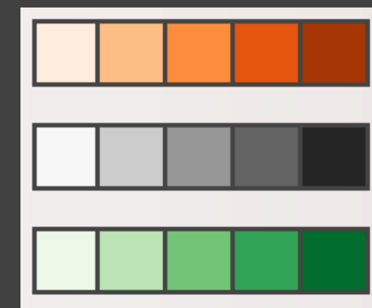
Useful when data has meaningful "midpoint"

Use neutral color (e.g., grey) for midpoint

Use saturated colors for endpoints

# Quantitative Color Encoding

## Sequential color scale



Ramp in luminance, possibly also hue

Typically higher values map to darker colors

## Diverging color scale

Useful when data has meaningful "midpoint"

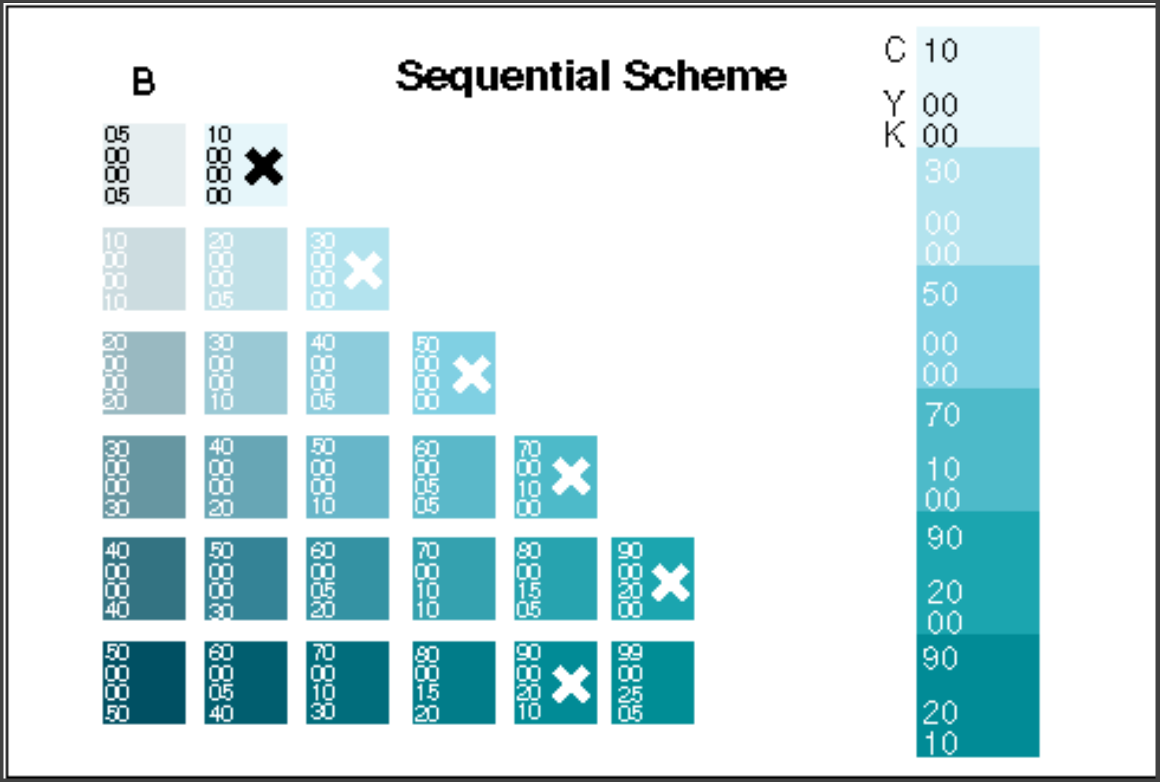
Use neutral color (e.g., grey) for midpoint

Use saturated colors for endpoints

## Limit number of steps in color to 3-9

# Sequential Scales: Single-Hue

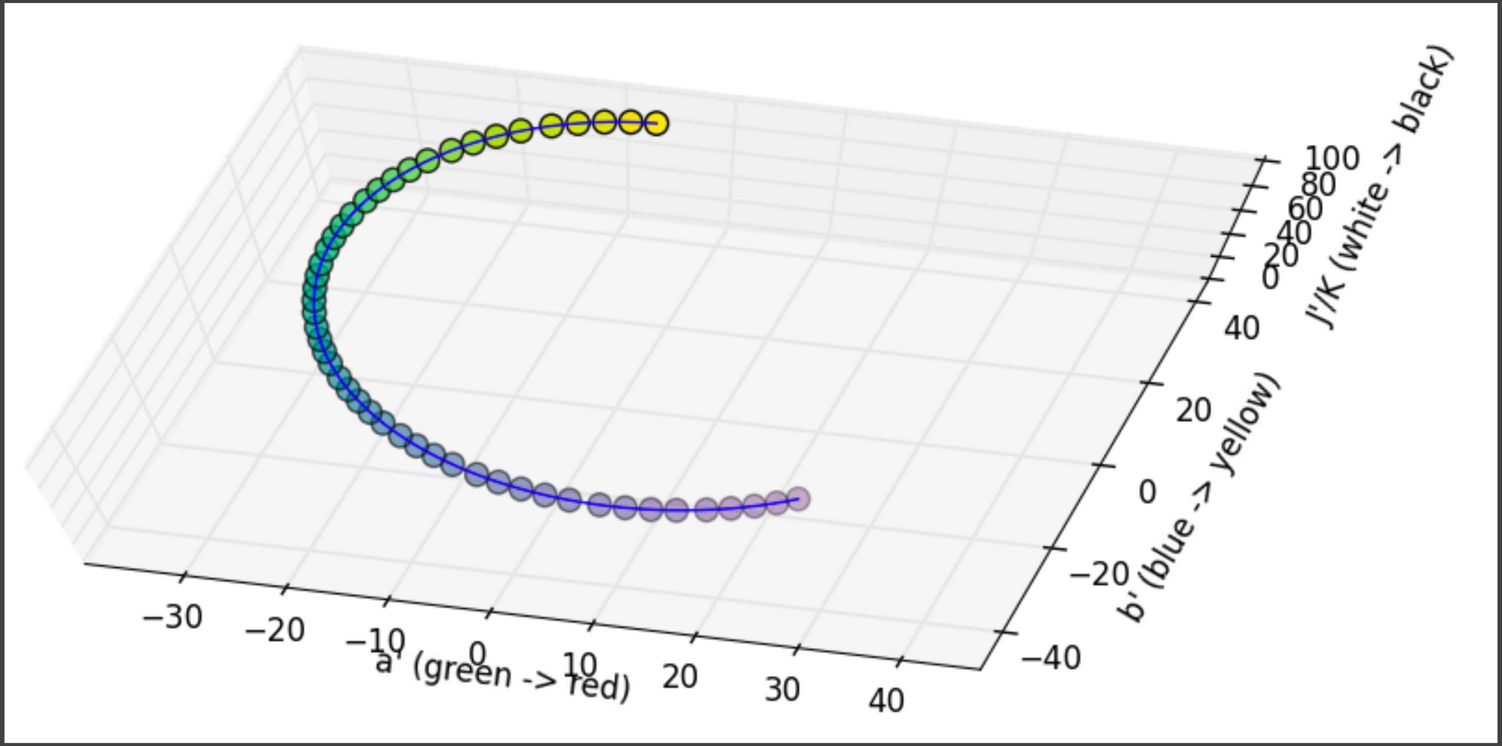
Ramp primarily in luminance, subtle hue difference



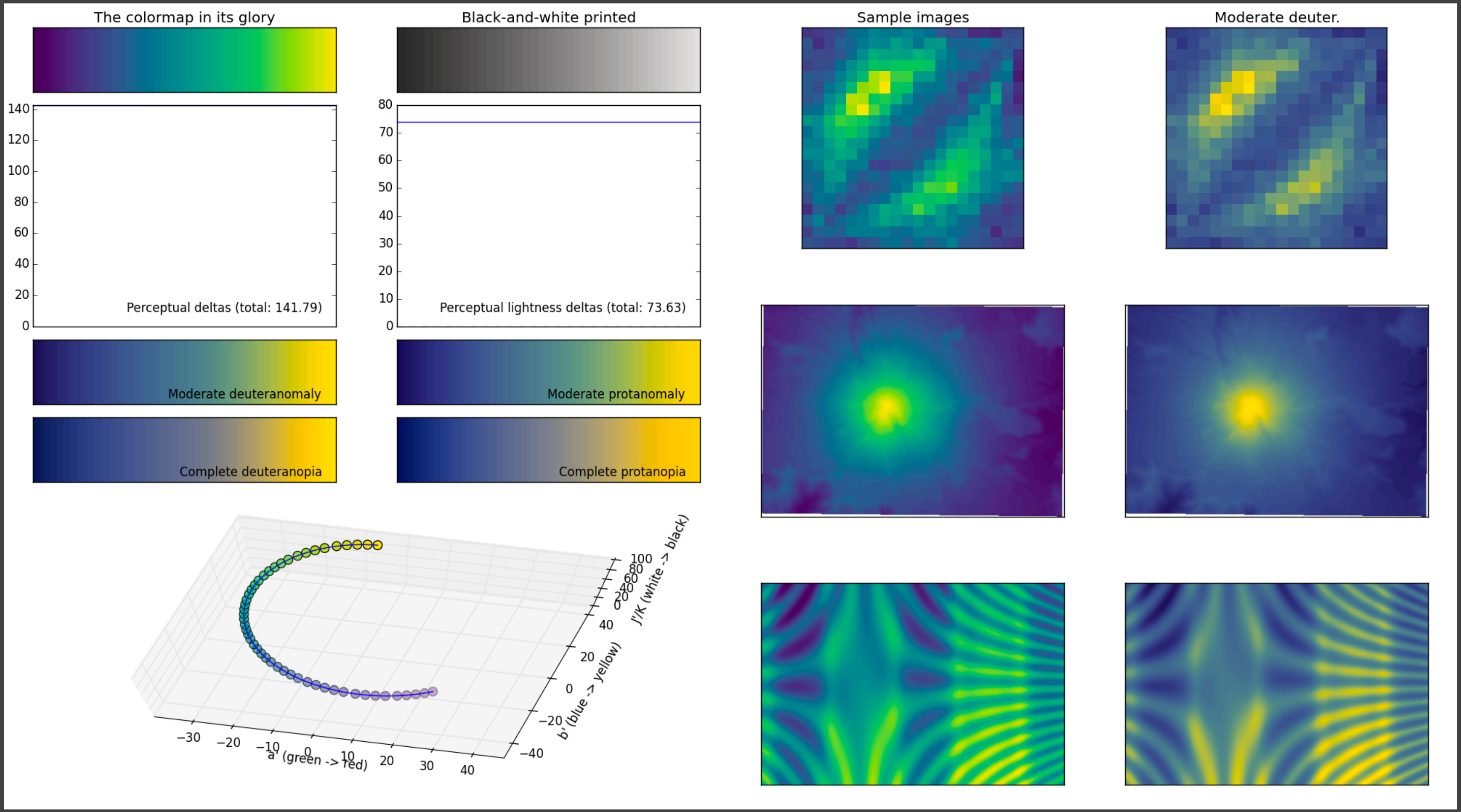

http://www.personal.psu.edu/faculty/c/a/cab38/ColorSch/Schemes.html

# Sequential Scales: Multi-Hue

Ramp luminance & hue in perceptual color space
Avoid contrasts subject to color blindness!

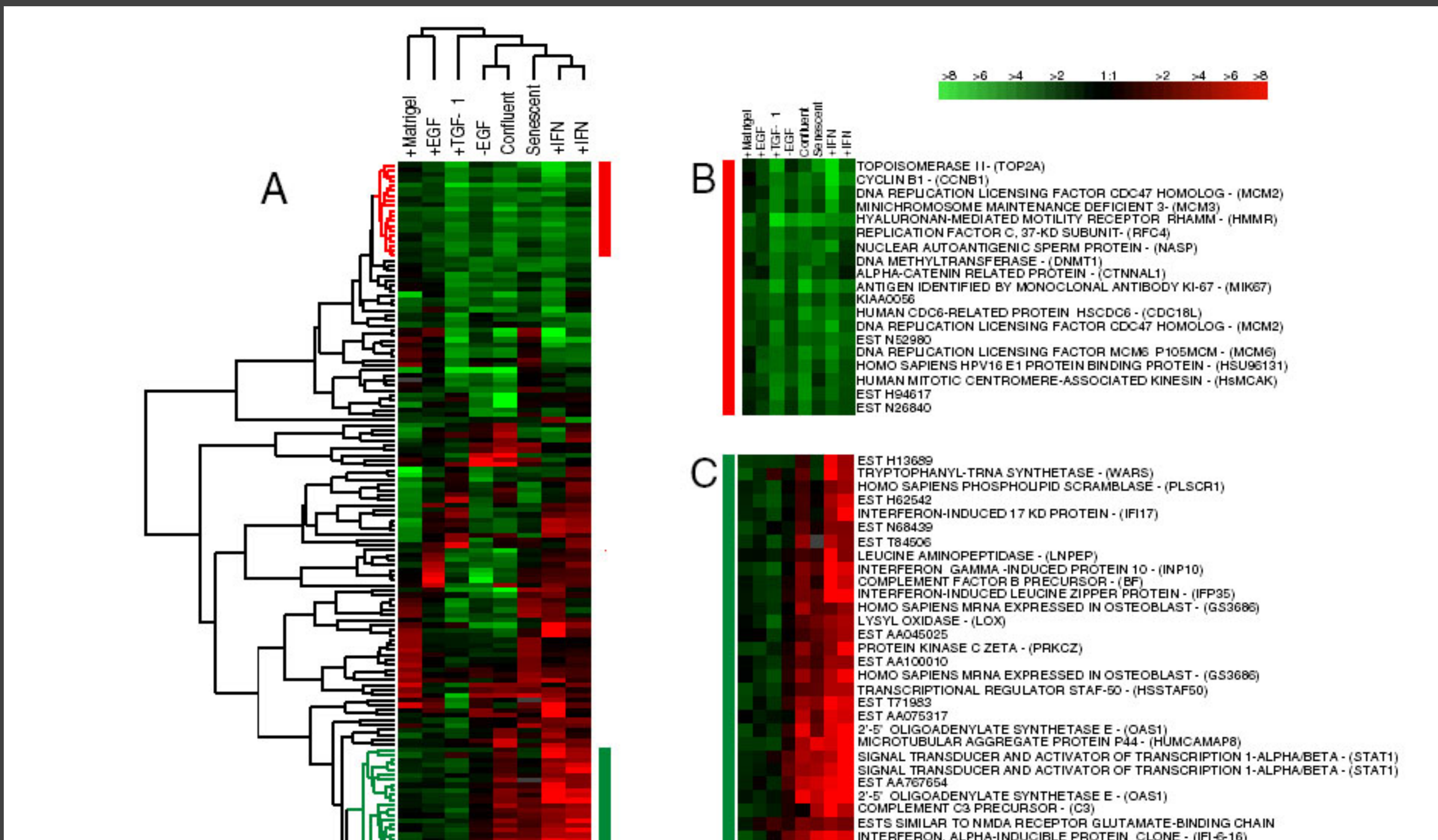


# Sequential Scales: Multi-Hue

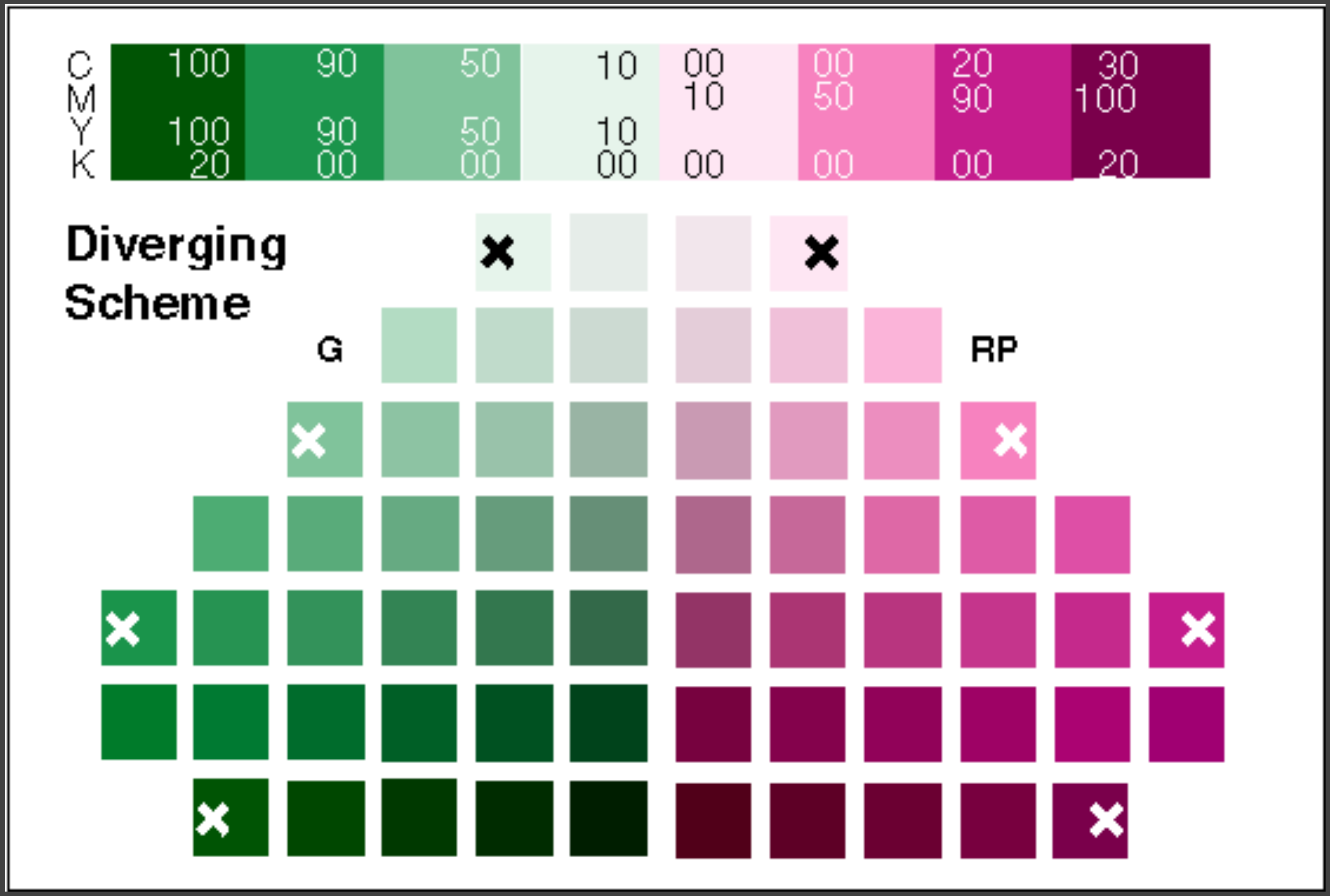



**Viridis**, https://bids.github.io/colormap/

# Diverging Color Scheme



# Designing Diverging Scales




http://www.personal.psu.edu/faculty/c/a/cab38/ColorSch/Schemes.html

# Designing Diverging Scales

**Hue Transition**

**Carefully Handle Midpoint**

Choose classes of values

Low, Average, High - Average should be gray

**Critical Breakpoint**

Defining value e.g., 0

Positive & negative should use different hues

**Extremes saturated, middle desaturated**

# Hints for the Colorist

Use **only a few** colors (~6 ideal)

Colors should be **distinctive** and **named**

Strive for color **harmony** (natural colors?)

Use **cultural conventions**; appreciate symbolism

Get it right in **black and white**

Respect the **color blind**

Take advantage of **perceptual color spaces**